ELECTRICIAN'S MATE 2c

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PREFACE

This book has been written for the use of enlisted men in preparing for advancement to the rating of Electrician's Mate 2c. The scope of the material presented here is designed to cover the qualifications necessary for advancement to Electrician's Mate 2c so far as it is possible to do so in writing, as distinct from the skill and practical factors to be gained from actual experience.

After a speedy review of the basic facts of electricity, this book goes into a full discussion of generators and motors, leading to sections on controls and circuit breakers. The course is rounded out with two chapters on A.C. motors and controllers and with a discussion of reactance and impedance.

As one of the NAVY TRAINING COURSES, this book represents the joint endeavor of the Training Publications Section of the Bureau of Naval Personnel and of those Naval establishments specially cognizant of the technical aspects of the Electrician's Mate's duties.

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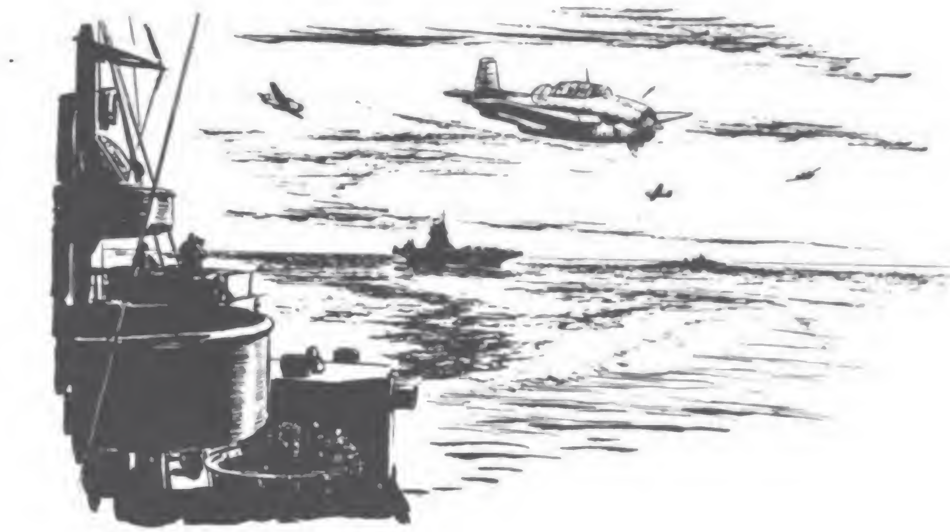


CHAPTER I

A QUICK REVIEW

SURE, YOU KNOW ELECTRICITY—

But in this book you're going to learn a lot more, so how about taking a quick look at what you already know? It won't do any harm—in fact, you ought to have a good review every so often anyway. But, watch this chapter—you'll travel at flank speed.

VOLTS, AMPERES, AND OHMS

Remember what happens when you hook up an ELECTRON PUMP—you call it a GENERATOR—to a conductor? The generator forces electrons into one end of the conductor, and just as many electrons get shoved out the other end of the wire.

The electromotive force (emf) which the generator puts on one end of the wire to make the electrons move is expressed in VOLTS. Voltage actually shows the DIFFERENCE in emf between two points in a circuit.

If ONE VOLT POTENTIAL causes a COULOMB of electrons to pass a point in the wire in a second, you have an AMPERE of

current flowing. Thus the ampere is the unit of measure of current flow PER UNIT OF TIME.

And the flow of electrons through a conductor is slowed up by the resistance of the metal. The moving electrons bump and rub against each other as they work their way from atom to atom in the wire. This resistance is expressed in OHMS.

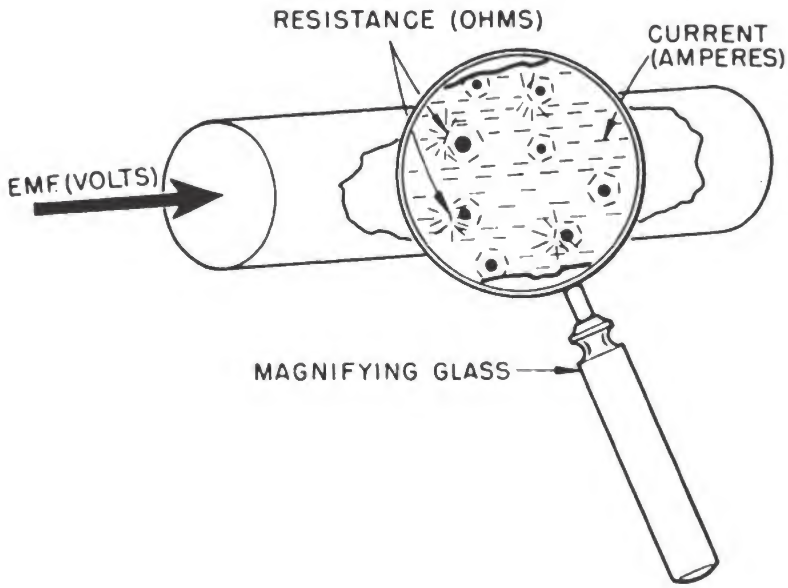


Figure 1.—Ohms, amperes, and volts.

Now to get ohms, amperes, and volts straight in your electrical mind, look at figure 1. Ohms = resistance; volts = electromotive force; and amperes = quantity of current per second. And don't forget the "per second" part on that definition of amperes.

Finally, be sure to remember that ELECTRONS move from negative to positive.

ATTENTION! WARNING!

Years ago, Ben Franklin jumped to the conclusion that the direction of an electrical current is from POSITIVE to NEGATIVE. Modern experiments have shown the real movement to be that of ELECTRONS—from NEGATIVE to POSITIVE. Nevertheless,

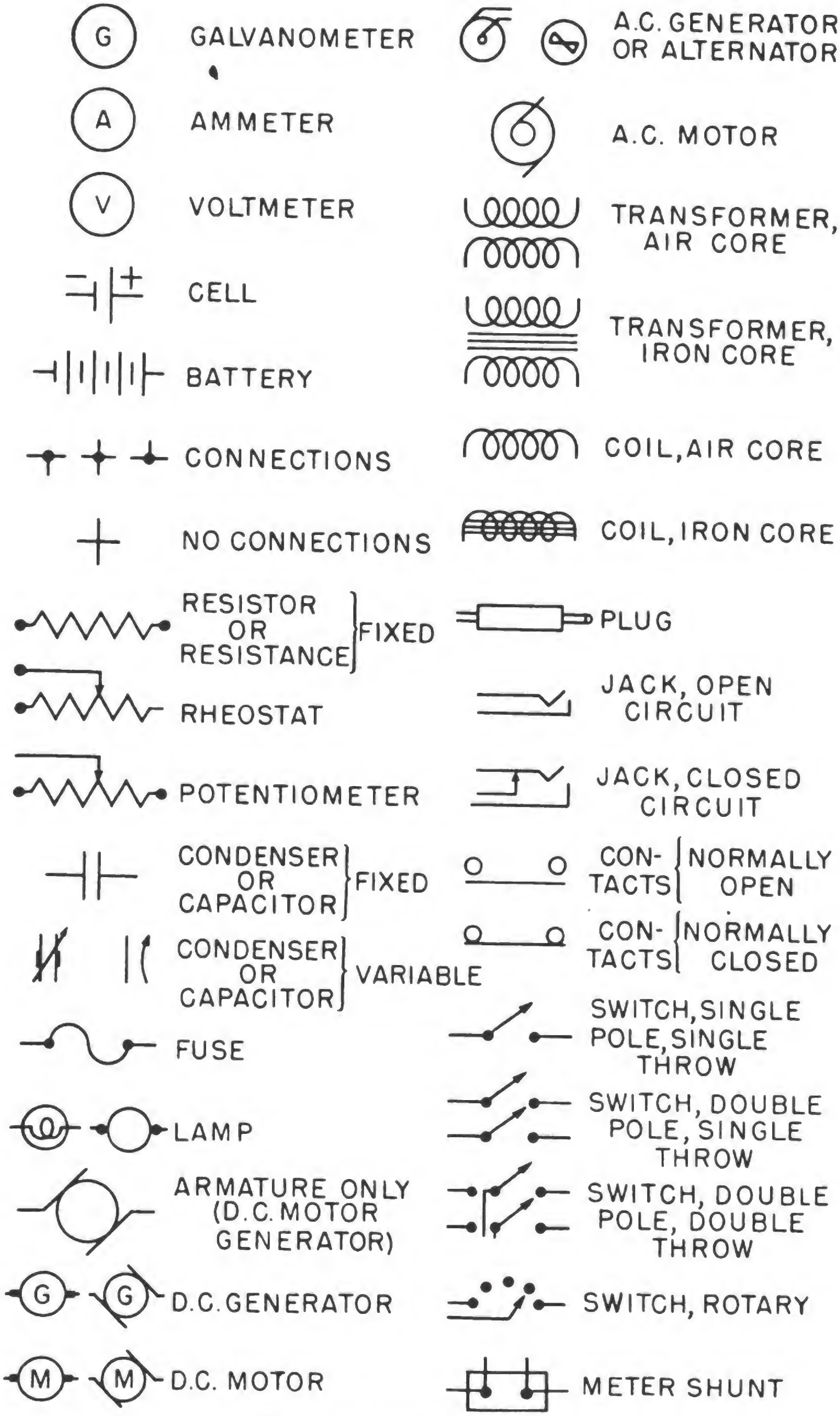


Figure 2.—Electrical symbols.

Franklin's theory is still used in many electrical textbooks and in some Navy manuals.

If you run across the old theory, DON'T let it confuse you. In those cases where you find that current is traced from positive to negative, simply use the OPPOSITE HAND from the one used in this book. Your answers will then be CORRECT.

And throughout this book all explanations are based on present-day knowledge—that electron flow is from NEGATIVE to POSITIVE.

ELECTRICAL SYMBOLS

Having come this far as an Electrician's Mate, you probably know all about electrical symbols and wiring diagrams. But it's a good idea to give them a quick review at this point. Glance over the chart in figure 2, and keep this chart in mind as a handy reference when you are studying wiring diagrams in later chapters of this book.

SERIES AND PARALLEL CIRCUITS

A quick glance at figure 3 will jog your thinking on the difference between SERIES and PARALLEL circuits.

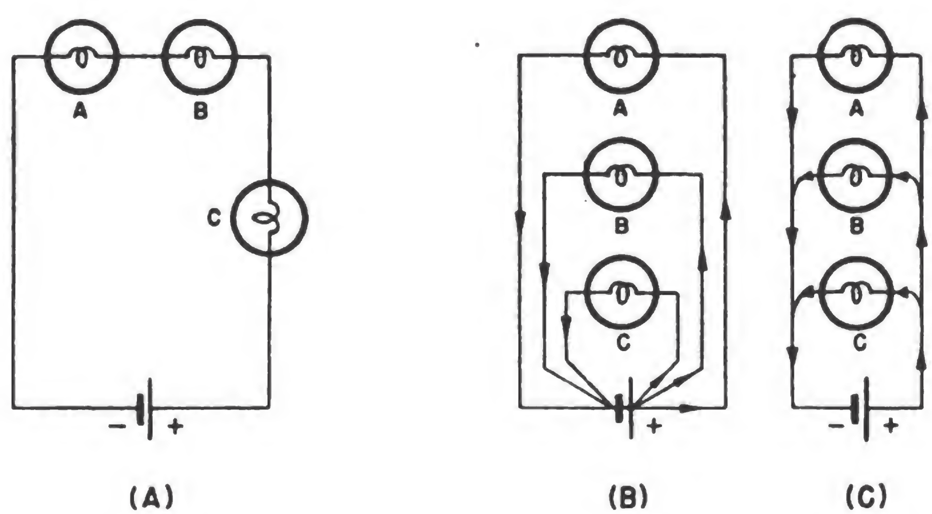


Figure 3.—(A) Series circuit; (B, C) parallel circuits.

Here's a handy set of rules to help you spot any circuit as being either SERIES or PARALLEL—

SERIES	PARALLEL
1. One path ONLY for current.	1. As many paths (branches) for current as there are devices in the circuit.
2. Every load dependent on other loads. If one device breaks down or is open, current to all the other devices is shut off.	2. Each load is independent of all the other loads. Used for many load circuits.
3. Each terminal has only one conductor attached. Current NEVER branches at series terminals.	

OHM'S LAW

Here's your old friend, Ohm, back again, this time with his famous law—

$$I = \frac{E}{R}$$

That formula is the mathematical way of saying that the total current through any circuit is equal to the total voltage of the circuit, divided by the total resistance in the circuit. Sure, you knew that! But don't forget—if you apply the law to a PART of the circuit, use the current, voltage, and resistance values for THAT PART. You know how fouled up the answers get when you use the wrong values.

You'll also recognize Ohm's Law when it's turned around—

$$E = IR, \text{ and } R = \frac{E}{I}$$

And it's only a short jump to the POWER EQUATION—

$$P = EI, \text{ or } P = I^2R$$

Don't forget—*P* is the power in WATTS.

METERS

You're logging the circuit to the after turret. Nope, you don't stick your finger in the socket and yell "*–()#*, chief, the blankety-blank so-and-so is full of amps., volts, and juice!" The chief in his usual gentle manner, would probably shake his head and say, "Gracious Harold, get out the ammeter, ohmmeter, and voltmeter, and give me a better answer than that."

Naturally, you use meters—and connecting them in the right lines and at the proper points will give you true readings. In figure 4*B* and 4*C*, for example, there are two RIGHT ways to

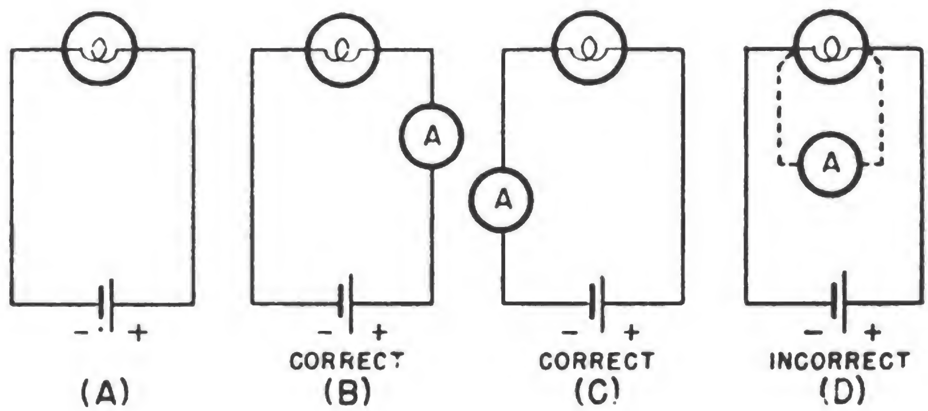


Figure 4.—Ammeter connections.

get an ammeter reading on the circuit of figure 4*A*, while connecting the ammeter up as in figure 4*D* is a fool-proof way to WRECK the meter in the shortest possible time.

If you want to measure the current through a complete circuit, figure 5*A* is your connection. But if you want only the current through the topmost load, the circuit of figure 5*B* will do the job.

And if you want to measure a current that you know runs between 50 and 70 amperes, you won't get to first base—you won't even get up to bat—by using an ammeter designed to measure currents between say, 0 and 3 amperes. But you don't have a 0–100 ampere ammeter. All right, use your 1–3

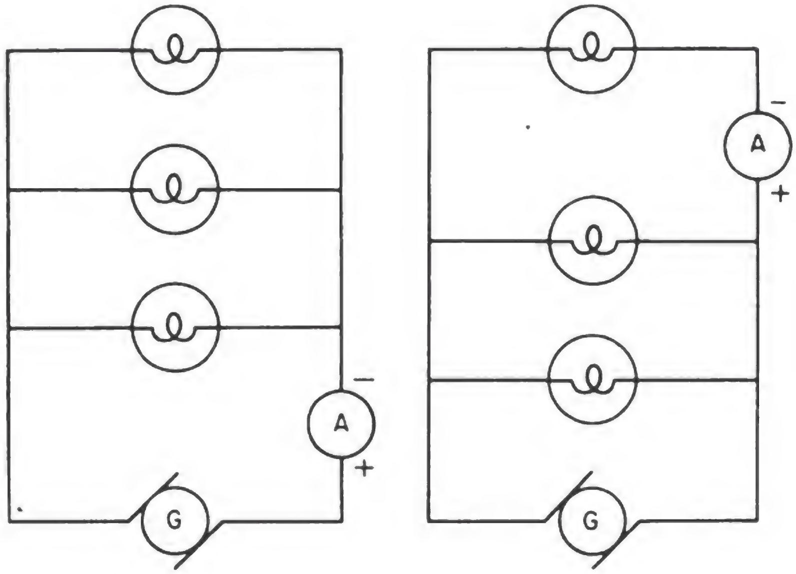


Figure 5.—A, Measuring total current through a circuit; B, Measuring the current through only one lamp.

ampere job—WITH A DIFFERENT SHUNT! The shunt will carry MOST of the current, allowing only a small fraction of the total to run through the meter.

FOR EXAMPLE—you have a 0–5 ampere meter, and you get a shunt that has only 1–100 the resistance of the meter. If you get a reading of 1.25 amperes on the meter, the current that is actually flowing in the main circuit is 125 amperes—

$$100 \times 1.25 = 125 \text{ amperes.}$$

Thus you have 100 times as much current going through the circuit as is going through the meter.

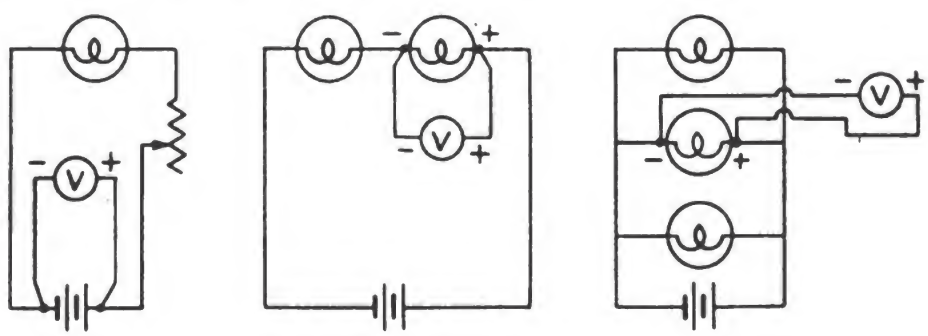


Figure 6.—Voltmeter connections.

VOLTMETERS are always connected ACROSS the two points whose voltage you want to measure. For example, *A* of figure 6 shows how to measure the battery or total voltage. But *B* and *C* measure the voltage across only one lamp. In using d.c. voltmeters, ALWAYS BE SURE to hook up the meter so that its positive terminal is connected to the plus (+) side of the cir-

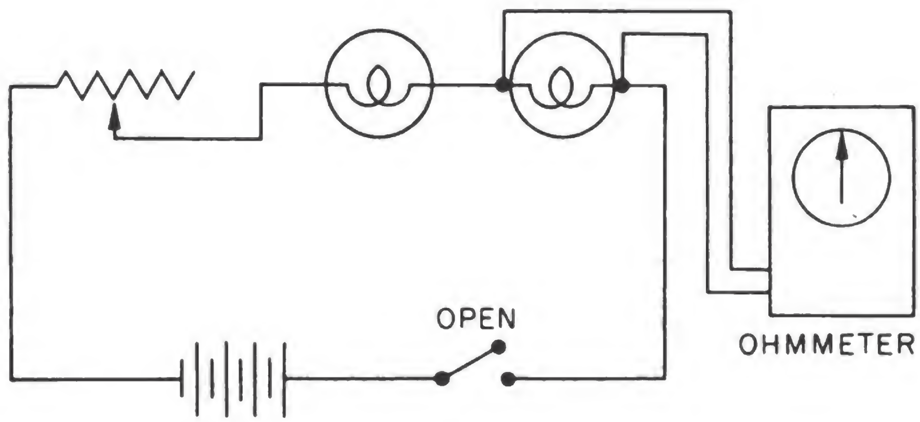


Figure 7.—Ohmmeter connections.

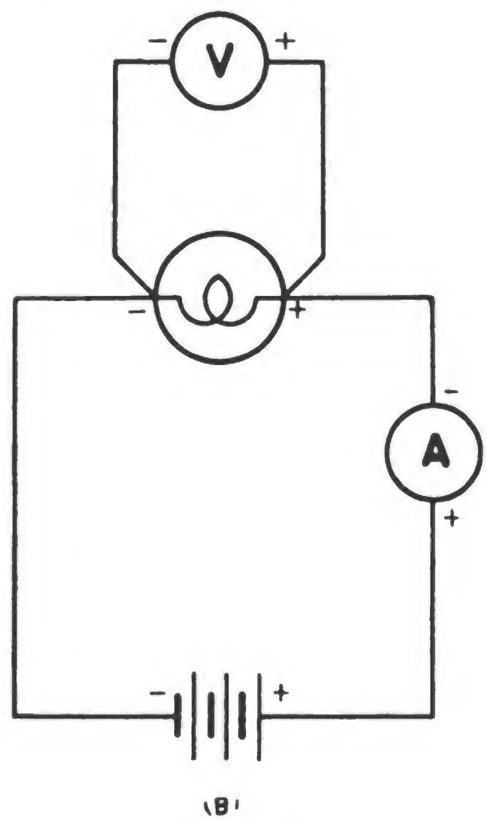


Figure 8.—Ammeter-voltmeter method of measuring resistance.

cuit, and its negative terminal is connected to the minus (—) side of the circuit. Reversed connections will make the meter read backwards. This is likely to bend the pointer.

To measure the RESISTANCE of a circuit, you can use an OHMMETER, connected as in figure 7, and get a direct reading in ohms. Or you can use an AMMETER-VOLTMETER COMBINATION, as shown in figure 8, and calculate the resistance by using Ohm's Law.

CIRCUITS

Here's a handy table to give you the voltage, current, and resistance formulas for series and parallel circuits—

GENERAL LAWS FOR SERIES AND PARALLEL CIRCUITS

	Voltage	Current	Resistance
Series.....	Total voltage squals sum of voltages across the parts — $E_T=E_1+E_2+E_3$, etc.	Current is the same in all parts — $I_T=I_1=I_2=I_3$, etc.	Total resistance equals the sum of the resistance of the parts— $R_T=R_1+R_2+R_3$, etc.
Parallel....	Voltage is the same across all parts of the circuit — $E_T=E_1=E_2=E_3$, etc.	Total current equals sum of currents in the different parts— $I_T=I_1+I_2+I_3$, etc.	The reciprocal of the total resistance is equal to the sum of the reciprocals of the resistance of the parts — $\frac{1}{R_T}=\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}$, etc.

KIRCHHOFF'S LAWS

Frequently you'll hit a direct current problem that is too complicated to solve by Ohm's Law. Then you use one or both of Kirchhoff's two laws to get the answer in a jiffy. Here are KIRCHHOFF'S LAWS—

ONE—AT ANY POINT IN A CIRCUIT AS MUCH CURRENT IS FLOWING TO THAT POINT AS AWAY FROM IT.

TWO—FOR A CLOSED CIRCUIT, OR A CLOSED SECTION OF A COMPLICATED CIRCUIT, THE SUM OF THE IR DROPS IS EQUAL TO THE APPLIED EMF.

You'll cover Kirchhoff's Laws carefully in Chapter 2.

MAGNETISM

Even the experts can't tell you exactly WHAT magnetism is. But they can tell you HOW it works and what it DOES.

Every magnet, even the earth, is surrounded by a FIELD OF MAGNETIC FLUX. These magnetic flux lines flow out of the north pole of the magnet, and flow back into the south pole. All magnetic fields may not be so simple as figure 9. But just remember that as you trace from *N* to *S* you are tracing out the lines of the field.

All magnetic fields follow three rules—(1) lines never cross, (2) all lines are complete from *N* to *S*, (3) in theory all lines leave at right angles to the magnet's surface.

Magnets can be either PERMANENT or TEMPORARY, depending on whether they hold the magnetism a long time or lose it quickly when the magnetizing influence is removed.

PERMEABILITY is a measure of the EASE with which magnetic flux passes through a material, while RELUCTANCE is a measure of RESISTANCE of a material to magnetic flux.

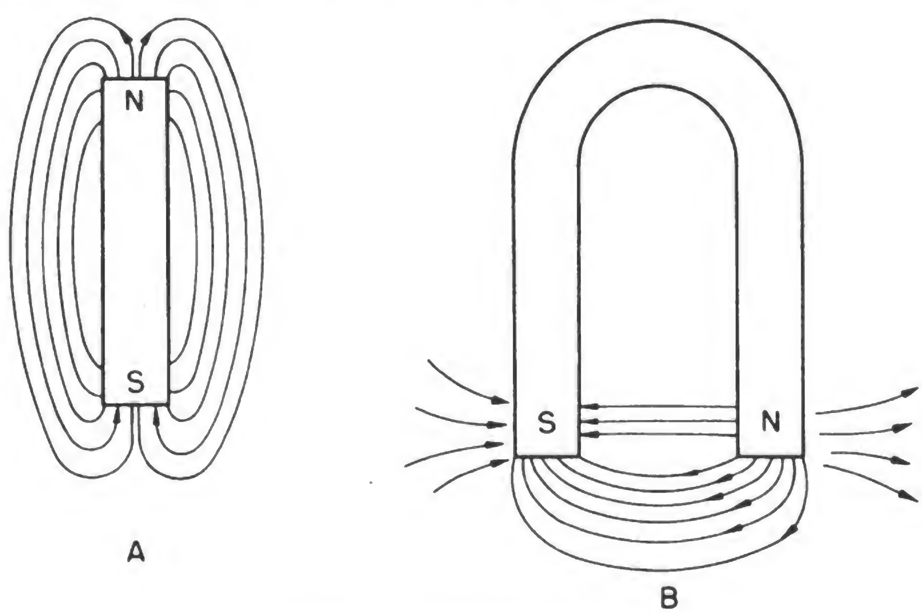


Figure 9.—Magnetic fields.

ELECTROMAGNETISM AND ITS USE

Run a CURRENT THROUGH A WIRE, and you PRODUCE A MAGNETIC FIELD around the wire, as indicated by the arrangement of filings in figure 10.

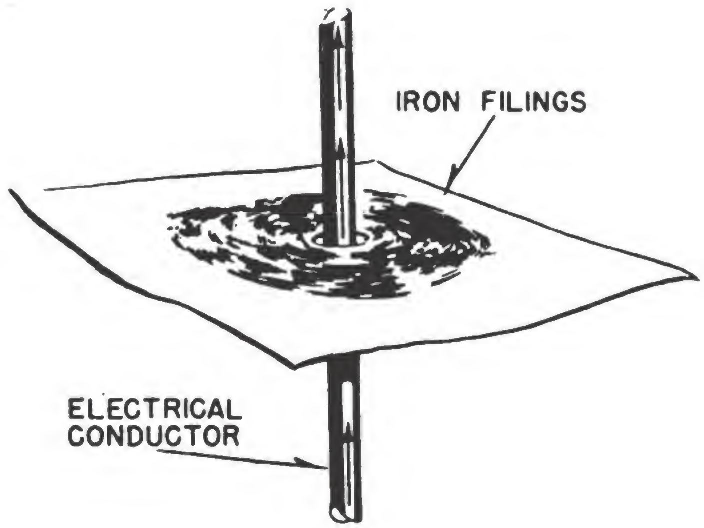


Figure 10.—Magnetic field around a conductor.

Likewise MOVE A WIRE up and down THROUGH A MAGNETIC FIELD, as in figure 11, and you INDUCE A CURRENT through the wire. Form the wire into a loop, and rotate the loop in the

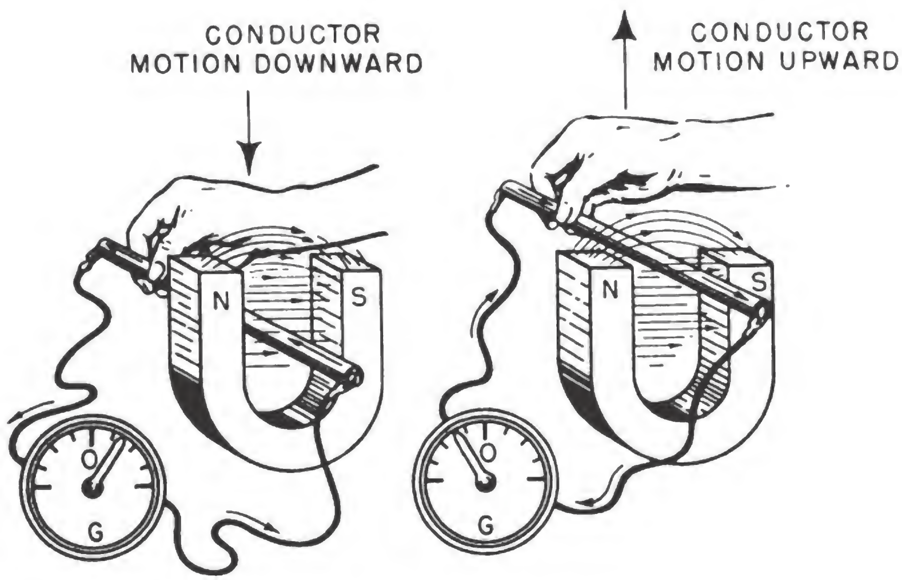


Figure 11.—Induced current.

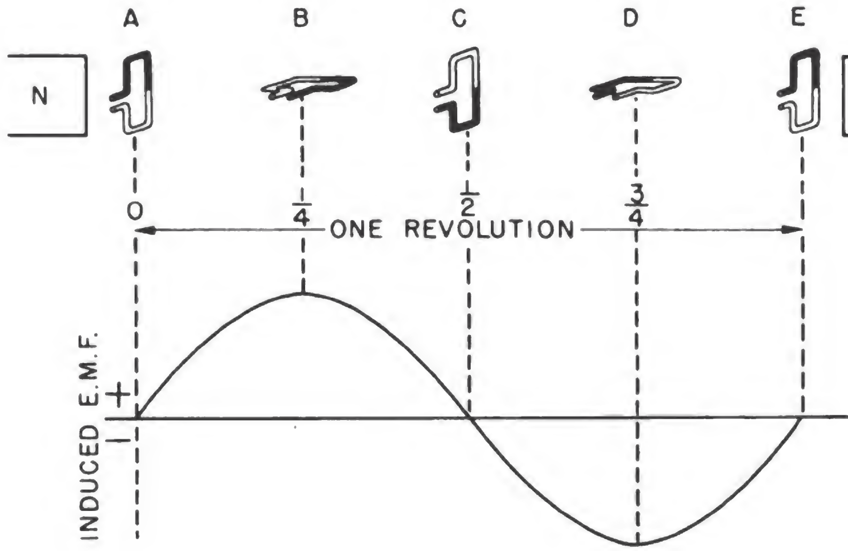


Figure 12.—Generation of a sine wave.

magnetic field, and you will generate an alternating current in the wire. The a.c. goes through a complete CYCLE, as in figure 12, each time a given conductor completes one revolution. The FREQUENCY of an alternating current is equal to the number of revolutions of the loop per second.

By using a split ring or COMMUTATOR, you can rectify the alternating current of the loop, and produce DIRECT current in the external circuit.

A d.c. motor is similar in construction to a generator. But in a motor, you feed current INTO the wire loop. The magnetic field of the loop with the stationary field of the poles produces TORQUE to turn the loop.

You use the HAND RULE to find the direction of the flux around a conductor. If you wrap your LEFT hand around the conductor, with your thumb pointing in the direction of current flow, your fingers will point in a direction of flux flow. (See figure 13*A*.)

You also use the hand rule for coils. To find the magnetic polarity of a COIL, wrap the fingers of your LEFT hand around the coil with your fingers pointing in the direction of current flow. Your thumb will then point to the north pole of the coil.

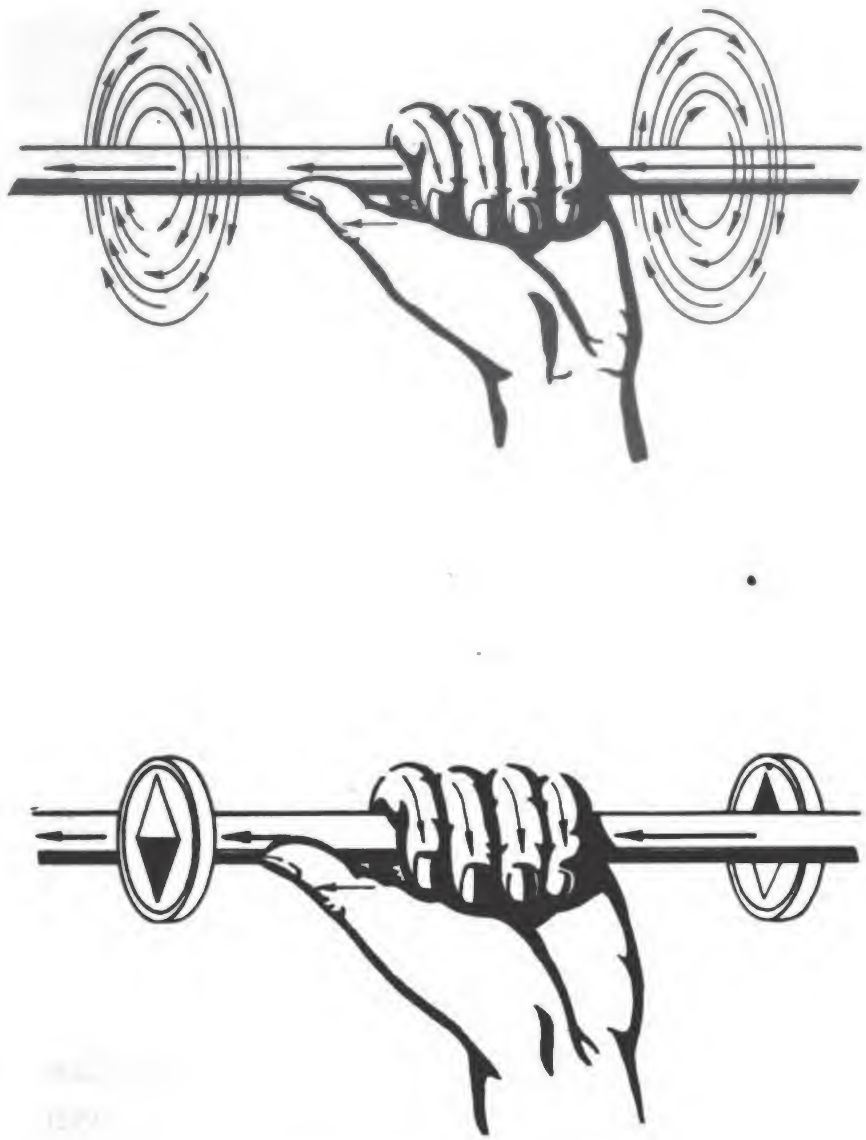


Figure 13.—Left-hand rule.

INDUCTANCE AND CAPACITANCE

INDUCTANCE is the property of a coil which makes it oppose any increase or decrease in current. The unit of inductance is the HENRY, named for Joseph Henry.

And when you use inductance, you'll think of Lenz's Law—THE MAGNETIC FIELD SET UP BY AN INDUCED CURRENT OPPOSES THE MAGNETIC FIELD THAT INDUCED THE CURRENT. Figure 14 is an illustration of the way this Law works.

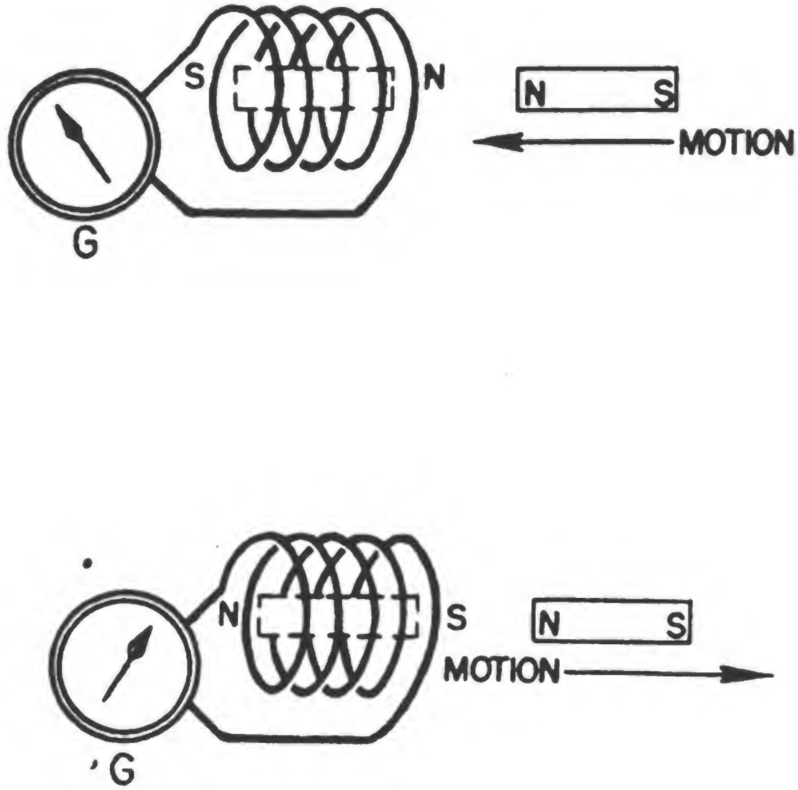


Figure 14.—How Lenz's Law works.

An electrical CONDENSER (or capacitor) has capacitance. Its action is like a rubber bag inserted in the side of a water pipe. When the water is flowing normally through the pipe, the bag contains only a little water. But a sudden surge or over-supply will cause the bag to fill up. It stretches and holds as much water as necessary to take up the surge. When flow decreases again, the bag slowly DISCHARGES into the supply.

In the same way, a condenser uses its capacity to oppose changes in voltage. The condenser is charged with current on the voltage surges and DISCHARGES its current as the voltage decreases. You can have either FIXED or VARIABLE condensers. The unit of capacity is the FARAD, C. The capacity of a condenser depends on several factors—such as surface area of plates opposite each other, type of material in the dielectric, and thickness of the dielectric.

TRANSFORMERS

You remember that a conductor carrying a.c. is surrounded by a magnetic field and will induce a voltage in a second conductor lying within its field. This principle is used in making a TRANSFORMER. If you have MORE turns of wire on the PRIMARY leg of the transformer core than on the SECONDARY leg, your transformer will STEP-DOWN the voltage. More turns on the secondary than the primary means a STEP-UP transformer.

And that's the end of the review! If you aren't clear on all points, pick up a copy of BASIC ELECTRICITY, NavPers 10622, and brush up.

CHAPTER 2

KIRCHHOFF'S LAWS

THEY CRACK THE TOUGH ONES

You've already heard about Kirchhoff's Laws, but do you know how to apply them? When you really KNOW Kirchhoff's Laws—and know how to USE them, you can solve ANY d.c. network, however complicated it may be. But it will require practice. So, to get you started off right, here is the first law, again—

FIRST LAW

IN A D.C. CIRCUIT AS MUCH CURRENT FLOWS AWAY FROM A JUNCTION POINT AS FLOWS INTO THE JUNCTION

In figure 15, the currents flowing away from junction A are labelled I_1, I_2, and I_3. The total current, I_T, is equal to the sum of $I_1 + I_2 + I_3$. Or, to say it another way—the algebraic sum of the current at a junction is equal to zero—

$$I_T - I_1 - I_2 - I_3 = 0$$

Let's get this "algebraic sum" business straight. In algebra, you give all numbers a positive or negative value. Then add all the negative numbers together, and subtract from the total of the positive numbers. The remainder is the ALGEBRAIC SUM. Here's an example—you have 31 dollars in your pocket and you owe 26 dollars. The 31 dollars is POSITIVE and the 26 dollars is NEGATIVE. Money in the pocket and money owed are certainly in OPPOSITE DIRECTIONS. The algebraic sum is a positive 5 dollars.

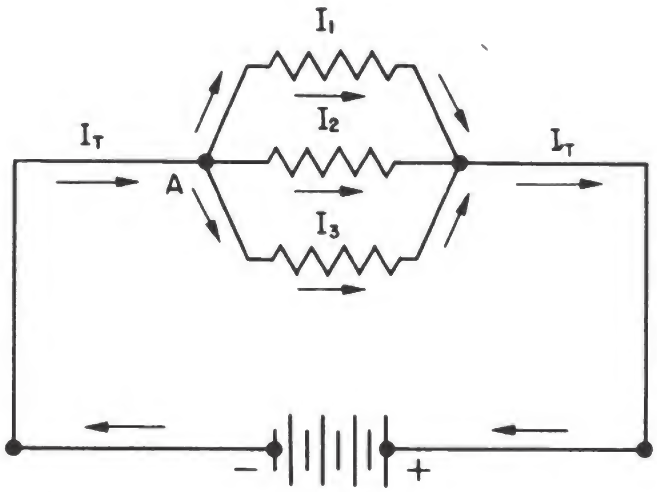


Figure 15.—Kirchhoff's First Law.

Now, exactly the same kind of adding is done in using Kirchhoff's First Law. All the currents flowing AWAY from point A,—I_1, I_2, and I_3—are NEGATIVE. And all the currents flowing TOWARD A,—I_T—are POSITIVE. So, all the negatives exactly balance the positives, and the algebraic sum is zero.

By now you're saying "Sure, that's a law of series circuits." So it is—because you're considering just ONE POINT in a circuit and of course, one point is in series with itself.

The big advantage in this Kirchhoff's Law is that you can always set down the facts of a circuit as a mathematical equation. And that's the way you'll USE the laws—making up your own equations. You'll learn how just as soon as you get the—

SECOND LAW

THE SUM OF THE IR DROPS IN A CLOSED CIRCUIT, OR ANY CLOSED PORTION OF A COMPLEX CIRCUIT, IS EQUAL TO THE APPLIED EMF.

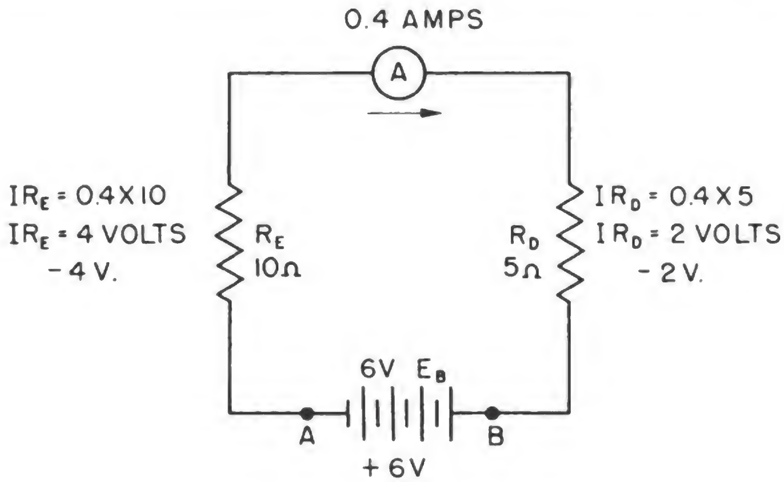


Figure 16.—Kirchhoff's Second Law.

Point *B* in figure 16 has a certain potential. Now, moving around the circuit, the sum of the IR drops across resistors R_D and R_E will be equal to the voltage applied by the battery.

You might look at Kirchhoff's Second Law this way. Voltage is applied to a circuit by generators or batteries. The loads of the circuit use up this voltage. And no matter how many sources you have or how strong they are—ALL the voltages are used up in the loads.

Stating Kirchhoff's Second Law mathematically—THE ALGEBRAIC SUM OF ALL THE VOLTAGES IN A CLOSED CIRCUIT OR ANY PORTION OF A CIRCUIT IS EQUAL TO ZERO. Now, which gets the positive sign and which the negative? Here are two good rules that will keep you straight—

Put a PLUS sign in front of each RISE in emf.

Put a MINUS sign in front of each DROP in emf.

Now look at figure 16 again. The current through the meter is 0.4. Remembering the two rules above, the IR drop across R_D will be—

$$0.4 \times 5 = 2 \text{ v.}$$

and across R_E—

$$0.4 \times 10 = 4 \text{ v.}$$

Labeling these IR drops negative, and the battery voltage (E_b) positive, you make up the following equation—

$$E_b - IR_D - IR_E = 0$$

Substituting,

$$6 - 0.4 \times 5 - 0.4 \times 10 = 0$$
$$6 - 2 - 4 = 0$$

Remember no matter how many IR drops are present in a circuit, the SUM of the IR drops about the circuit subtracted from the applied E always equals ZERO.

HERE'S HOW—

To use Kirchhoff's FIRST Law, you must analyze enough junctions so that you include every unknown current at least once.

To use Kirchhoff's SECOND Law, you must apply it at least once to EACH branch in the network.

To set up a problem for solution by Kirchhoff's Laws here are the steps you must go through.

First —Draw the circuit diagram, label everything, and put in all the GIVEN quantities.

Second—Indicate with arrows the direction the current is flowing. As in figure 17, I_T shows the total current in the circuit. I_A shows the current through R_A, and I_B the current through R_B. Remember—

$$I_T = I_A + I_B$$

Third —Count the number of unknowns you have, and set up the SAME number of equations to solve for the unknowns. Be sure each equation contains an expression that you have NOT used in any previous equation.

Finally—You can use algebra to solve the equations.

WHICH DIRECTION?

It doesn't matter which direction you select for the current arrow. If you choose the wrong direction the answer for total current will come out with a MINUS sign. Then you'll know that the current in that circuit flows in the OTHER direction.

TRY A PROBLEM

You connect a generator to feed two loads in parallel. The current drawn is 7 amperes. Resistance A is 30 ohms, and resistance B is 40 ohms. Ignore the resistance within the generator and the leads. The generator voltage, E_g, is 120 volts. What is the current through each resistance?

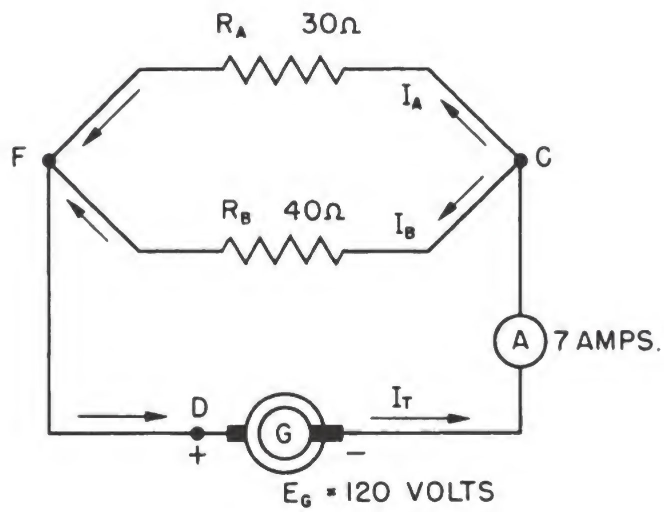


Figure 17.—Problem circuit.

The circuit is shown in figure 17, with the known values labelled. You know that the current divides into I_A and I_B at junction C. And these two currents joint at F to form current I_T again. So, at C, by Kirchhoff's First Law—

$$I_T - I_A - I_B = 0$$

Next, start at A, and move through the generator, around the circuit and through the upper resistance R_A. By Kirchhoff's Second Law—

$$E - 30 \times I_A = 0, \text{ or } I_A = \frac{E}{30}$$

Then, move from A through the generator and resistance R_B—

$$E - 40 \times I_B = 0, \text{ or } I_B = \frac{E}{40}$$

Now, put these values for I_A and I_B into the First Law equations—

$$I_T - I_A - I_B = 0$$

or $$7 - \frac{E}{30} - \frac{E}{40} = 0$$

and $E = 120\text{v}\ (E_g)$

substitute, $E = 120$

Finally, in $$I_A = \frac{E}{30}$$

then, $I_A = 4$ amp.

Likewise, $I_B = 3$ amp.

AND HERE'S A TOUGHER ONE

You connect two storage batteries in parallel to feed a 2-ohm lamp bank, as in figure 18*A*. Battery *A* has an emf of 6 volts, with 0.15 ohm internal resistance. Battery *B* has an emf of 5 volts, with 0.05 ohm internal resistance. What's the current through the batteries, and the current in the lamp bank? Ignore wire resistance.

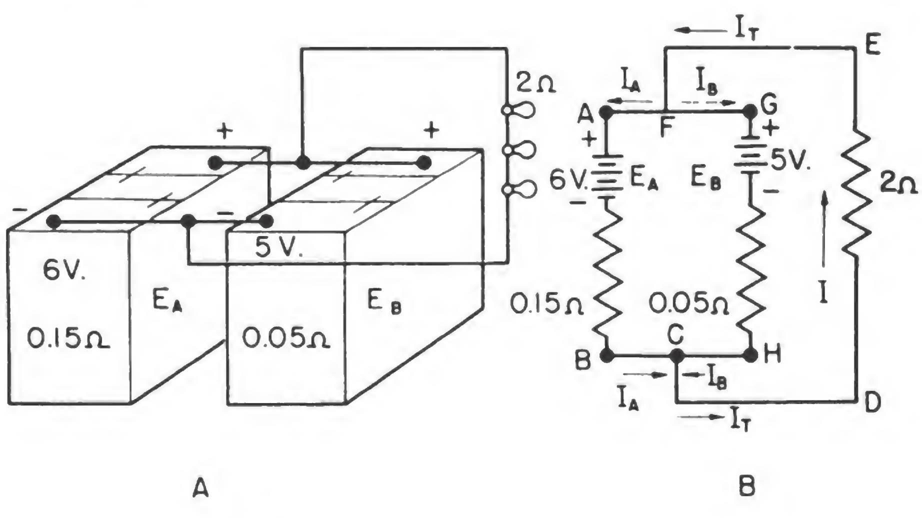


Figure 18.—Kirchhoff problems.

First—draw a circuit diagram and put on the given information, including the internal resistances of the batteries. Label the unknown currents, and put on assumed direction for the currents. Here are three of these unknown currents—I_T,

I_A, and I_B. But $I_T = I_A + I_B$. So you get rid of one unknown, because you know that the current through the lamps is $(I_A + I_B)$.

To simplify the mathematics still further, let A represent I_A and B represent I_B.

Next—analyze circuit ABCDEFA—

$$6 - 0.5 \times I_A - 2(I_A + I_B) = 0$$

and $\quad 2.15 \times I_A + 2I_B = 6 \ldots\ldots$

Then—analyze circuit GHCDEFG—

$$5 - 0.05 \times I_B - 2(I_A + I_B) = 0$$

$$2 \times I_A + 2.05I_B = 5$$

Now—solve these two equations simultaneously, and you get—

$$I_A = 5.64 \text{ amp}$$

$$I_B = -3.06 \text{ amp}$$

What's that minus sign doing in the answer for I_B? Right! I_B is flowing opposite to the way you picked.

Finally, since $I_T = I_A + I_B$

$$I_T = 2.58 \text{ amp.}$$

The fact that I_B is opposite to your selected direction tells you that current from battery B is really flowing through battery A and not the lamp. Look at figure 18 again. If the arrows through battery B are reversed—then battery B is being CHARGED. Thus, battery A is furnishing power to both the lamp and battery B. Just looking at the diagram, you'd GUESS that both batteries were furnishing power to the lamp. But Kirchhoff's Laws tell you what is REALLY happening. That is, both the lamp and battery B are getting power from battery A.

HERE IS ANOTHER

This one is about connecting generators in parallel. It demonstrates an important principle, so work it carefully. Two generators are connected in parallel as illustrated in figure 19. The voltages, resistances, and assumed paths of current are as indicated. Find the individual currents, the total currents, and the direction of current flow.

Assume first that—

$$I_T = I_1 + I_2$$

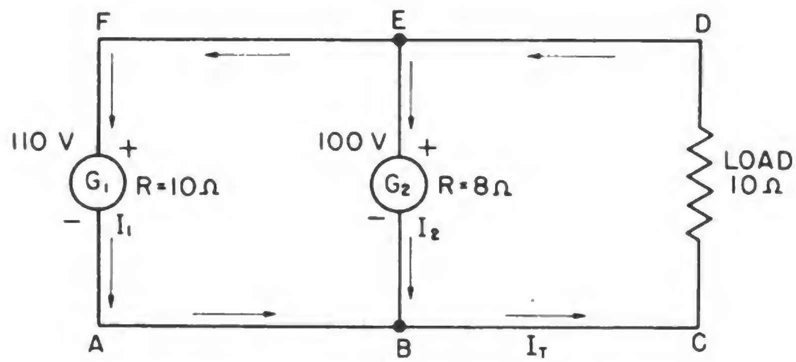


Figure 19.—Kirchhoff's Law applied to two generators in parallel.

Now trace the circuit ABCDEFA, and apply Kirchhoff's Second Law—

$$110 - 10 \times I_1 - 10(I_1 + I_2) = 0$$

Combining terms, $-20 \times I_1 - 10 \times I_2 = -110$

Applying Kirchhoff's Second Law to circuit BCDEB, you get—

$$100 - 8 \times I_2 - 10(I_1 + I_2) = 0$$

Combining terms: $-10 \times I_1 - 18 \times I_2 = 100$

Then solve these equations simultaneously—

$$-20 \times I_1 - 10 \times I_2 = -110$$
$$-10 \times I_1 - 18 \times I_2 = -100$$

You will find— $I_2 = -3.46$ amps.

$I_1 = 7.23$ amps.

$I_T = 3.77$ amps.

The negative sign (—) before the I_2 current indicates that the current is flowing BACKWARD through the generator, G_2, while the total current through the load is less than the current carried by G_1.

This little problem shows you what will happen if you try to parallel generators, without having their output voltage matched. You will hear more about this later.

ANOTHER PROBLEM

The problem illustrated in figure 20 is typical of many that you may be asked to solve. Find the total resistance of the circuit, the total current, and the current through each resistor.

The first step in solving this problem is to combine the SERIES resistors *R4*, *R5*, and *R6*. When you have done this, redraw the circuit as in figure 20*B*.

Next combine the series resistors $R4$, $R5$ and $R6$ with the parallel resistor $R2$, and draw the circuit shown in figure 20C. Notice that you now have three resistors in series, so that the total resistance of the circuit is only 100 ohms.

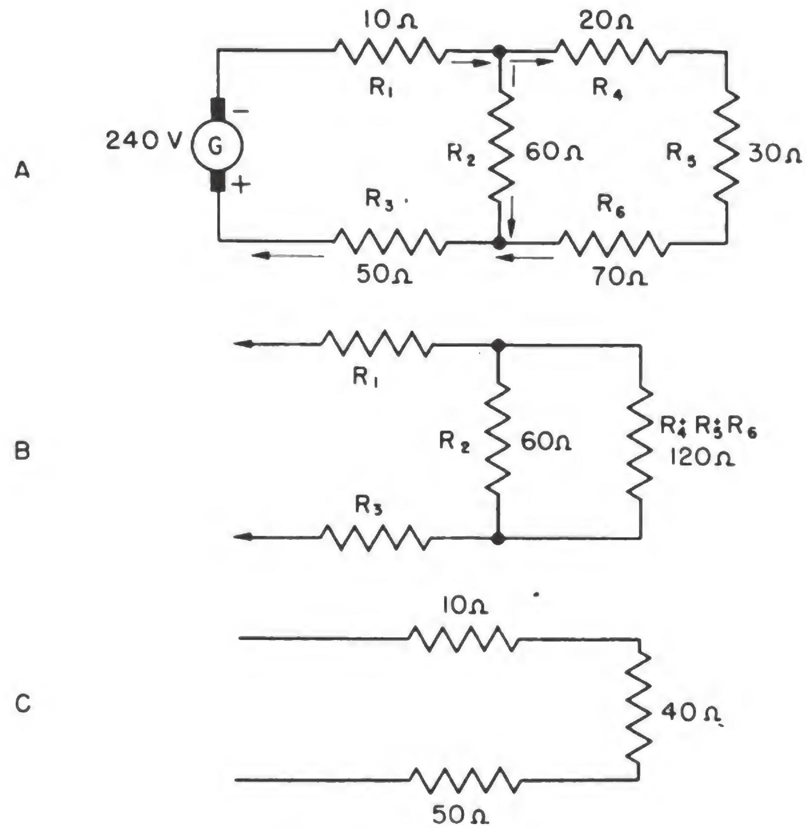


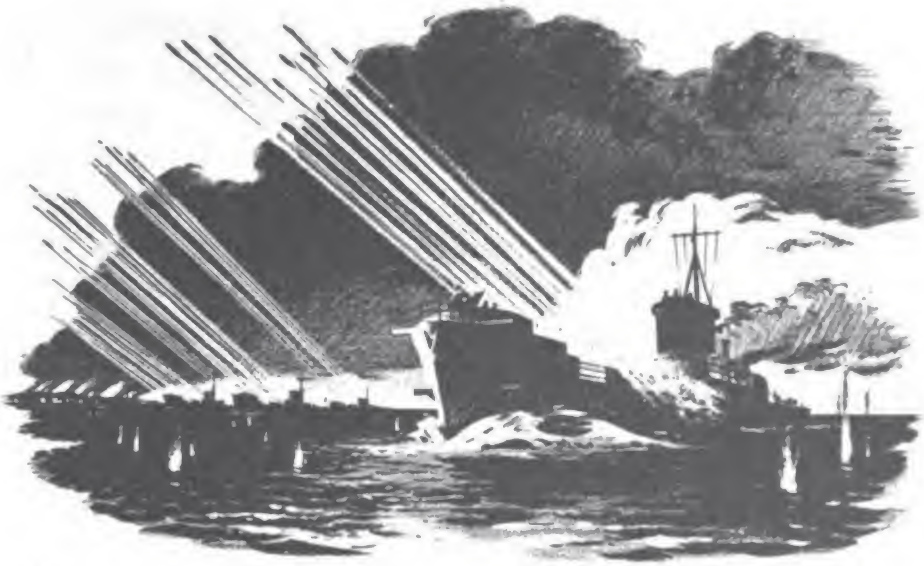
Figure 20.—A resistance network.

Now for the current. The applied E is 240 volts, and the

TOTAL current is— $\dfrac{240}{100} = 2.4$ amp.

Since the resistance of $R4$, $R5$, and $R6$ is parallel to the resistance of $R2$, 0.8 amperes will flow through $R4$, $R5$, $R6$ and 1.8 amperes through $R2$. But how about $R1$ and $R3$? These two resistors are IN SERIES with the generator and carry the full load of 2.4 amperes.

You will find many more problems like these. The more of them you work the easier they become.



CHAPTER 3

MEASUREMENT INSTRUMENTS

HOW MUCH, WHERE?

Electricity is an intangible substance. You can't see it, but you can see what it does. You can't pick it up and carry it away, but you can FEEL its presence if you get your finger tangled into a live circuit.

Since you can't SEE DIRECTLY what is going on within a circuit, you must use MEASURING DEVICES—such as VOLTMETERS, AMMETERS, and WATT METERS—to tell you what is happening to the electricity flowing within the wires.

You learned a great deal about these meters from your training course on *BASIC ELECTRICITY*. If you're a little rusty on the subject, go back to that manual again before going on in this chapter.

Good electricians use instruments the way a good doctor uses his stethoscope—to find out what goes on inside the circuit, to measure how much electricity goes where. Know your instruments, and they'll do most of your work for you. They're accurate and quick.

AMMETERS

You remember that one form of D. C. AMMETER is a combination of a GALVANOMETER (figure 21) and the correct SHUNT to handle the current to be measured. This type of meter will measure d.c. only, since the alterations of a.c. reverse the meter torque too fast for the needle to follow.

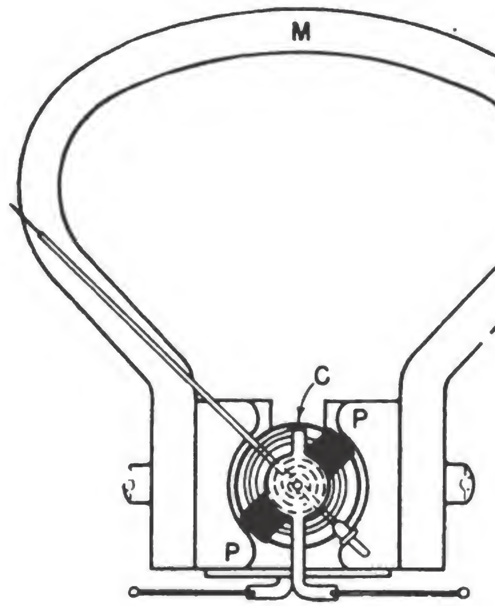


Figure 21.—Moving coil, or D'Arsonval, galvanometer.

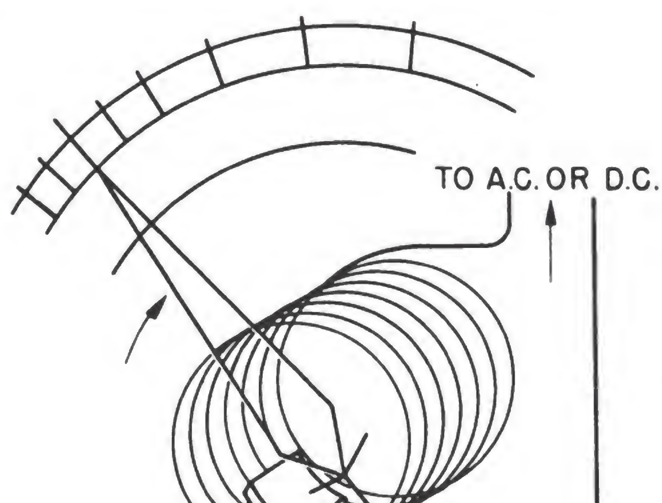


Figure 22.—Iron-vane movement.

To measure A.C., you use an ammeter having either an IRON-VANE MOVEMENT or an ELECTRODYNAMOMETER mechanism (figure 22). In both of these ammeters, current transformers carry most of the current to protect the fine wire coils.

Most of the portable d.c. ammeters with ranges up to 30 amperes, and the switchboard ammeters with ranges up to 50 amperes have BUILT-IN SHUNTS. You must use EXTERNAL SHUNTS when you wish to measure larger currents.

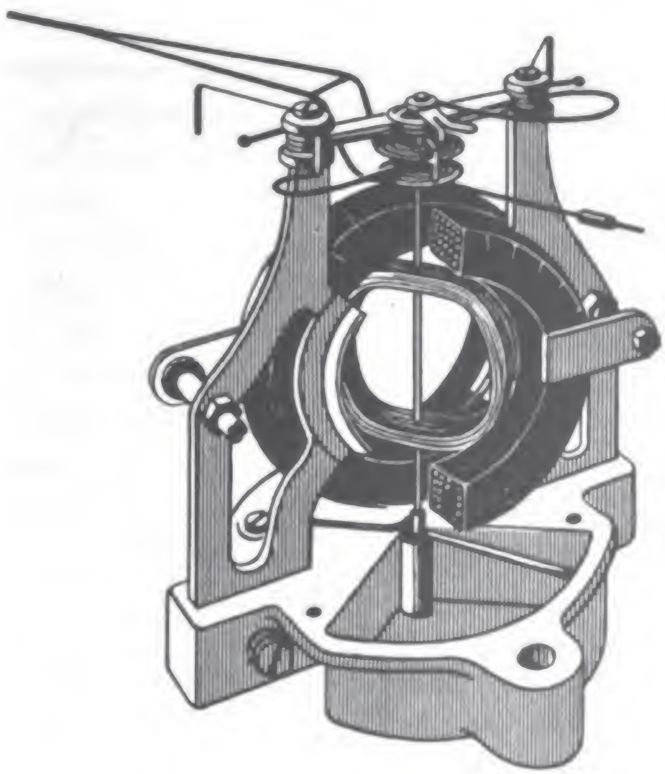


Figure 23.—Electrodynamometer movement.

When you use shunts, be sure to use the RIGHT one with each ammeter. And use only the shunt leads that come with the meter, since the leads are part of the shunt circuit. If you use other leads or change the length of the leads, you'll foul-up the calculation of the instrument. The meter is then less accurate because the ratio between shunt and meter resistance is upset.

Be sure the connections at the ammeter and the shunt are TIGHT and CLEAN. Dirty or loose connections add resistance to the meter circuit and result in a false reading.

INSTRUMENT TRANSFORMERS

Ammeters and voltmeters for a. c. are usually coupled to the line by a transformer. This protects both the operator and the instrument from high a.c. voltages. Also, by using transformers, ordinary 0-5 amp. ammeters and 0-150v voltmeters can be used to measure most higher a.c. values.

POTENTIAL TRANSFORMERS have step-down windings and are used to measure voltage. The primary is connected across the line, and the secondary is connected across the voltmeter terminals.

CURRENT TRANSFORMERS have step-up windings. The primary of the transformer has VERY FEW windings, and is connected INTO the line. Since this is a step-up transformer, the CURRENT flowing in the SECONDARY is lower than the primary current. Therefore, an ammeter with a LOWER RANGE can be used to measure indirectly the current flowing in the primary.

All this is fine as far as the meter is concerned, but it makes the meter circuit extremely dangerous when it is opened. The transformer is designed for practically short-circuited operation—with the secondary flux cancelling the primary flux. If the secondary is opened (by removing the ammeter), this cancellation disappears. And the secondary acts like an ordinary step-up.

It produces a dangerously high voltage across its terminals. Operators are guarded against this high voltage by grounding and short-circuiting switches in the meter circuit. NEVER RE-

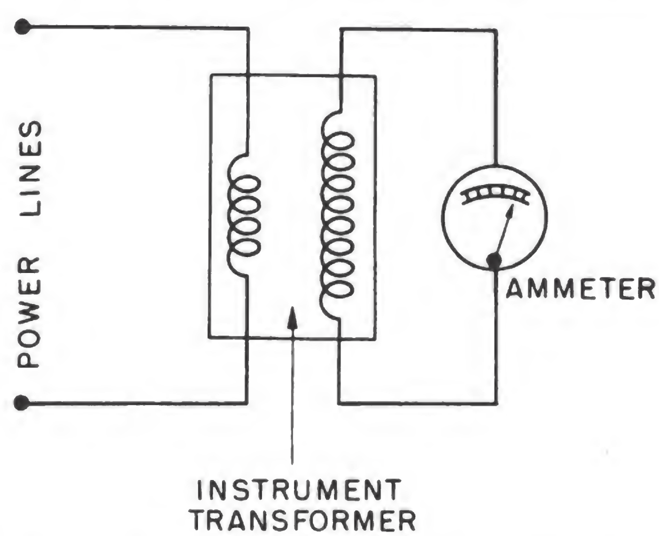


Figure 24.—Instrument transformer connections.

MOVE AN AMMETER FROM THE SECONDARY OF A CURRENT TRANSFORMER UNLESS THE SECONDARY IS SHORTED THROUGH A SHORTING JUMPER AND THROUGH A GROUND.

Figure 24 shows the connection of a current transformer and its meter.

Suppose the current through the power line is 1,000 amp. Then you'd select a current transformer with a step-up ratio of 1:200. You might have two turns on the primary and 400 on the secondary. Then your meter would get 1/200th of 1,000, or five amperes, in its circuit.

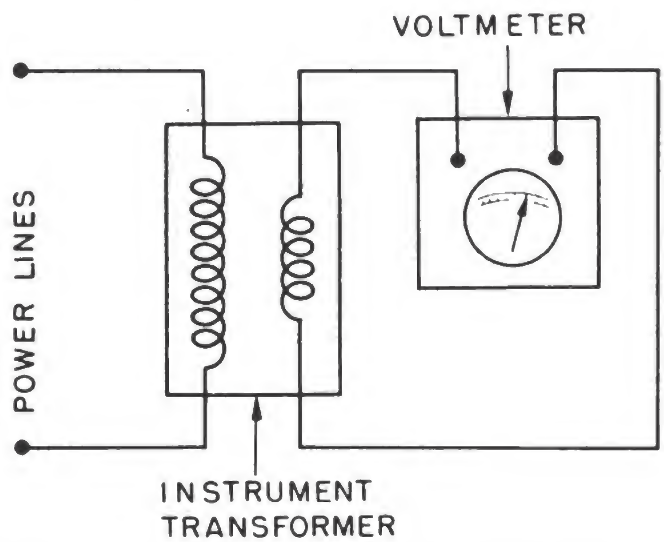


Figure 25.—Instrument transformer connections.

In figure 25, let's say that the voltage across the power lines is 2,200 volts, and your instrument transformer has a ratio of 1:20. Then the meter would have 1/20th of 2,200, or 110 volts, across the terminals.

Meters using instrument transformers are usually found in switchboards, and are calibrated to read either the line voltage or current, whichever the case may be. You won't have to worry about the transformer ratio except in the case of repair or replacement. But remember these three things about instrument transformers—

ALWAYS GROUND one side of the secondary to protect the instrument, and to safeguard yourself against injury in case the insulation between primary and secondary breaks down.

NEVER OPEN the secondary of a CURRENT transformer while the primary is loaded. You will get a tremendous voltage across the terminals. Keep the secondary shorted when it's not connected to a current coil.

NEVER SHORT the secondary of a VOLTAGE transformer. Close the secondary only through a HIGH resistance, such as a voltmeter. And be sure the secondary is open when the primary is energized.

AMMETER PRECAUTIONS—READ CAREFULLY

You always connect an ammeter, or a current transformer primary, IN SERIES with the line carrying the current. That is really IMPORTANT. NEVER connect CURRENT-MEASURING instruments ACROSS THE LINE or between any two points where there is a potential difference of more than a few milli-volts. The resistances of meter coils, shunts, and transformer coils are purposely made low to avoid a large voltage drop when you connect them in series in the line.

It's up to you to BE SURE that the meter you choose has a range GREATER than the maximum line current. Don't guess! Be sure! Meters cost more than fine watches.

VOLTMETERS

VOLTMETERS are basically the same as ammeters, such as the ammeter of figure 21, except that a great amount of resistance is added in series with the voltmeter movement.

You can even use an AMMETER as a VOLT METER by being careful to add enough resistance in SERIES. BUT DON'T TRY THIS WITHOUT PROPER SUPERVISION. Added resistance reduces the current through the meter coil. For example, you have an ammeter that gives full-scale deflection with 0.01 ampere in the moving coil. The coil resistance is 20 ohms. If you want to use this meter to measure VOLTAGE across a line carrying a maximum of 220 volts, here's how. Find out how much resistance is needed to protect the meter—that is, how much resistance is needed to keep the current down to 0.01 ampere—by using Ohm's Law—

$$R = \frac{E}{I} = \frac{220}{0.01} = 22{,}000 \text{ ohms.}$$

But since you already have 20 ohms resistance in the meter, you simply add 21,980 ohms resistance IN SERIES with the meter movement. The correct connection is shown in figure 26.

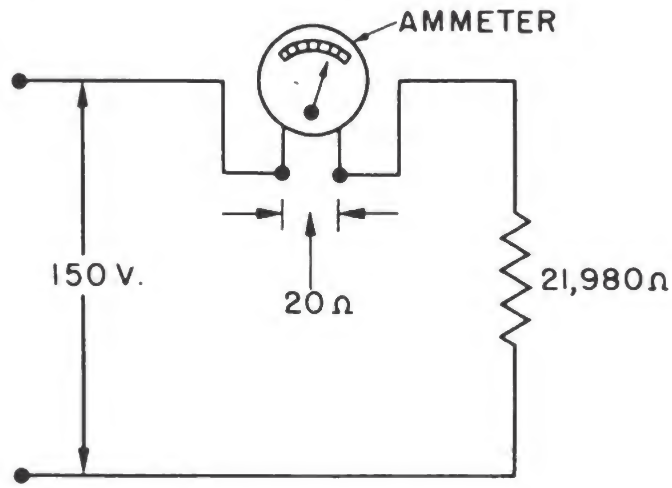


Figure 26.—Using an ammeter as a voltmeter.

Voltmeters for a.c. usually use the iron-vane mechanism. For high-precision voltage measurements on either a.c. or d.c., you use a voltmeter with an electrodynamometer movement.

Be careful to connect the voltmeter in series with its added resistance, and if a voltage transformer is used connect it across the two points whose potential difference you want to measure.

If you're using a multi-range voltmeter, first be sure that the meter has a HIGHER range than the voltage to be measured. Start with the highest range on the meter and work down to a range that gives a deflection on the upper half of the meter scale.

MULTIPLIERS

By doubling its resistance with MULTIPLIERS, a voltmeter will read twice the range. You can also use multipliers to get even larger increases in range. FOR EXAMPLE, you can make a 150-voltmeter read voltages up to 600 volts by connecting an EXTERNAL RESISTOR in series with the meter. This resistor, called

a MULTIPLIER, must have three times as much resistance as the meter, in this case. Then the scale reading will be multiplied by 4.

In contrast to ammeter shunts, MULTIPLIERS have high resistances.

WATTMETERS

Most WATTMETERS have an electrodynamometer movement (figure 23) and are calibrated to indicate TRUE POWER. You see the circuit diagram and connections for a wattmeter in figure 27.

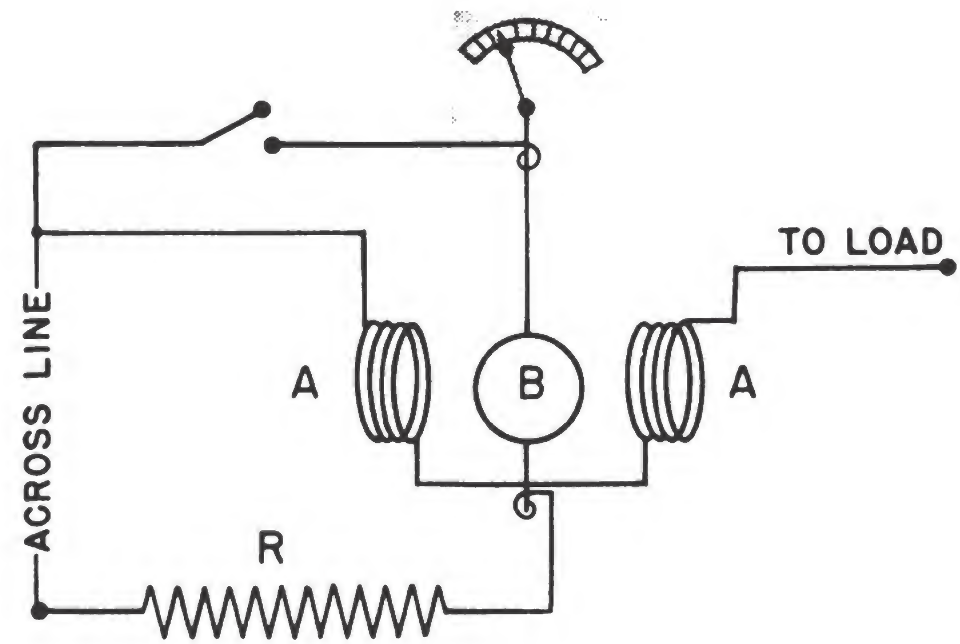


Figure 27.—Wattmeter connections.

POLYPHASE WATTMETERS

In polyphase circuits the power can be measured by using a separate wattmeter for each phase. This is the most accurate method, but it's not the most practical. It's easier to use a wattmeter built to measure the combined power of the polyphase circuit. This meter has two sets of stationary current coils mounted on the frame, and two movable coils mounted on a single shaft. There is no electrical connection between the

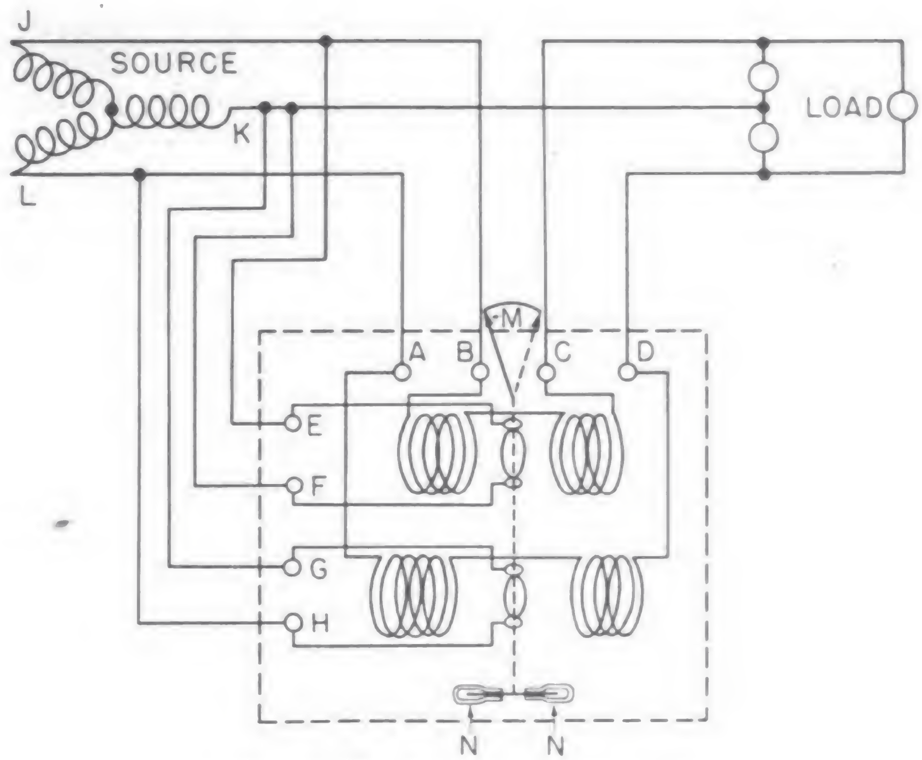


Figure 28.—Polyphase wattmeter.

phase circuits. The TORQUE on the shaft is the SUM of the individual torques produced by each of the movable COILS.

Figure 28 shows a three-phase wattmeter connected to a three-phase line. Notice that there are eight connections to the power lines. In this particular meter some of the leads are combined so that fewer jumpers are led out. However, if you count the meter terminals, you'll find that eight separate connections are made.

Sounds pretty complicated, doesn't it? Well, it is, and for this reason all polyphase wattmeters have a connection diagram on their name plate. Use this diagram for properly connecting any particular polyphase wattmeter.

WATTMETER PRECAUTIONS

When you use a wattmeter, take ALL the precautions already mentioned for ammeters and voltmeters. In addition. MAKE SURE that neither the current nor the voltage exceeds the wattmeter capacity. Test the circuit with a voltmeter and an ammeter BEFORE you connect the wattmeter. The POINTER DEFLEC-

TION of a wattmeter does not assure you that the instrument is not overloaded—because the pointer indicates only TRUE POWER. And, if either E or I is low, P will still be low enough to keep the wattmeter pointer below full-scale deflection. To all appearances the meter is not over-loaded. BUT, suppose E is very low and I is very high. This results in low power indication, P, but in the meantime the high current is cooking the stationary coils—AND YOU GET NO WARNING FROM AN OFF-SCALE DEFLECTION. The same kind of damage would be done to the movable coil if you were dealing with a high E and a low I. TEST THE CIRCUIT with a voltmeter and an ammeter BEFORE connecting the wattmeter.

Normally, you won't need to use a wattmeter to determine the power in a d.c. circuit. You can easily calculate the power by measuring the voltage and current—

$$P = EI$$

WATT-HOUR METERS

You're familiar with this meter which measures electrical work (or electrical energy)—the product of POWER and TIME. You are going to run into an increasing number of watt-hour meters aboard ship, so you will need to know what they are. Watt-hour meters, whether for a.c. or d.c., are tiny electric motors that run at a speed proportional to the amount of POWER through the meter. Therefore, POWER, in watt-hours, is proportional to the rpm of the motor.

The D.C. WATT-HOUR METER can be of either the commutator type or the mercury-pool type. The current is delivered to the armature of the motor either by a commutator or through a pool of mercury.

The A.C. WATT-HOUR METER, which is the one you'll use most frequently ashore, uses a tiny induction motor. This is an aluminum disk rotating between the poles of two magnets, one with a voltage winding, the other with a current winding. These two windings cause a shifting flux which applies a total torque on the disk in proportion to the true power in the circuit. To prevent the disk running away as a motor, a damping mag-

net reduces the rpm and makes the speed proportional to the line power. Thus, the speed is a measure of true power, and the number of revolutions is a measure of *T* (time). A set of indicator dials geared to the disk records the total kilowatt-hours of power passed through the meter circuit.

A.C. CIRCUIT FACTORS

Now you come to three instruments that can give you the characteristics of the A.C. in a given circuit. The instruments are the POWER FACTOR METER, the SYNCHROSCOPE, and the EXCITATION INDICATOR. Each does what its name says. However, a description of how they work will have to wait until you know more about a.c. and phase angle, and other principles to be covered in the chapter on a.c. You'll learn more about these meters in chapter 18.

METER CARE AND ADJUSTMENT

Except for adjusting the movement so that the needle reads ZERO when no current, voltage, or resistance is on the meter, KEEP YOUR HANDS OUT OF THE INSTRUMENTS. Electrical instruments are fine precision devices, finer than most watches. When an instrument goes bad, send it to the man who knows—the instrument repairman. He's trained for the job, and he has the necessary special tools.

You can and should set the needle at ZERO when the instrument is idle. This insures an accurate reading when you energize the instrument. But you don't have to open up the instrument to adjust the needle. The screw on the front of the meter directly above the pivot point lets you adjust the setting without wrecking the instrument.

Here are factors that can upset the accuracy of a d.c. meter—

Temperature.
Vibration.
Stray magnetic fields at the instrument.
Exposure to intense magnetic fields which may damage the permanent magnet.
Moisture, dirt, and corrosion.
Overloads.

Poor mechanical balance of the moving coil.

Bent pointer, or warped or shifted scale.

Electrostatic charges built up on the glass scale cover by wiping with dry cloth. Use what you have learned about the correct method of polishing a meter.

And here are some factors, in addition to the ones just listed, which may affect a.c. meters—

Voltage and frequency variations.

Variation in power factor.

Abnormal wave shapes.

Variations in instrument transformer characteristics.

The Navy supplies you with first-class instruments built to stand pretty strenuous service. But don't mistreat or abuse these instruments. Give them the best of care, and they'll give you the best of service. When you connect a portable meter, never leave long drapes of wire trailing out over the work bench or the deck. And never hammer or bang on a bench on which a meter is lying. The vibration is bad for the works, jewels, and indicator. Insulate switchboard and panel instruments with pads and bumpers if any severe vibration is present in the panel. Protect instruments from extremes of heat or cold. And—

Keep your fingers out of the works! Let the instrument repairman do the overhauling.

CHAPTER 4

GENERATORS—ARMATURE WINDINGS

FIRST, A SHORT REVIEW

As an EM you should know quite a bit about generators. At least, you should know these things—what a generator is, what it's main parts are, and the ways of connecting a generator.

First—generators are machines which convert mechanical energy into electrical energy.

Next—the two essential parts of a generator are the ARMATURE and the FIELD. The armature is the rotating part. It carries the conductors which cut the magnetic field. The generator voltage is induced in the armature conductors. This induced voltage is delivered to the load circuit by a commutator and brush system. The commutator-brush system does two things—it furnishes a slipping connection between the rotating armature and the stationary load; and it rectifies the induced a.c. of the armature coils, delivering d.c. to the load circuit. The field furnishes the flux to be cut by the armature. It consists of two, four, six or any other multiple of two pole pieces wound with electromagnetic windings.

And—there are five ways of connecting generators, shown in figure 29—

The SHUNT connection—the armature and field are in parallel. This is the generator with the drooping voltage curve, figure 29 (1).

The series connection—the armature and field are in series. This is the generator with the rising voltage curve, figure 29 (2).

The CUMULATIVE COMPOUND connection—the armature is connected to two field windings, one in series and one in parallel, figure 29 (3). The windings carry current in the same direction and thus help each other produce the flux field. This generator can have a rising, a drooping, or a level-voltage curve.

The DIFFERENTIAL COMPOUND connection—the armature is connected to two field windings, one in series and one in parallel. But the two windings carry current in opposite directions, figure 29 (4). They oppose each other and produce a weaker field. This is the generator with a full drooping voltage curve.

The SEPARATELY-EXCITED connection—the armature has no connection with its own field, figure 29 (5). This generator may have any kind of a voltage curve depending on the field adjustment.

ARMATURE WINDINGS

The armatures of generators are wound in two different ways—LAP WINDING and WAVE WINDING. When you know these two types of windings, you'll have armatures licked. But before going on with these types of winding, get squared away on two general features of armatures—drum winding and coil span.

DRUM WINDING

All commercial armatures, both lap and wave-wound, use a DRUM WINDING. For this winding you need a core of iron shaped like a drum (figure 30). This is the first step in build-

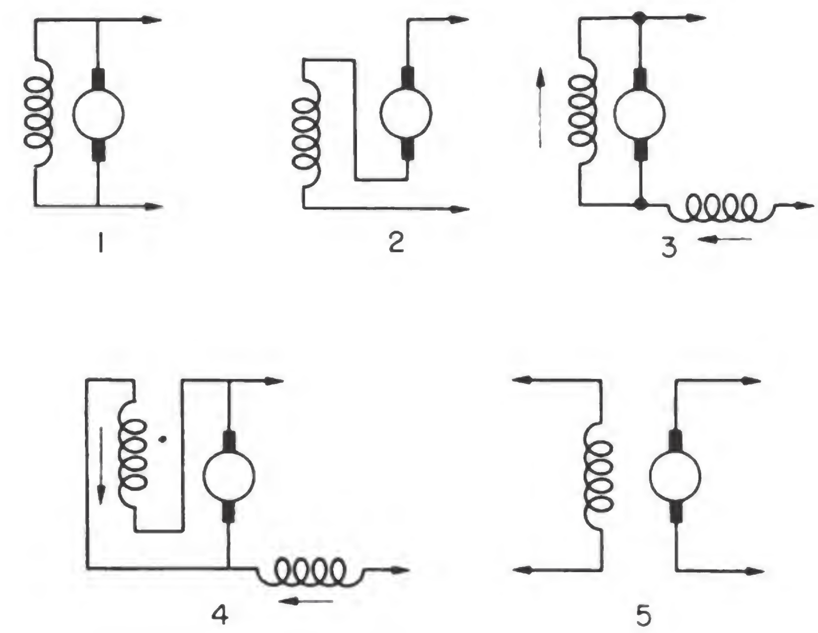


Figure 29.—Generator connections.

ing up an armature. Notice that the slots are all ready to receive the windings. The core is laminated to cut down eddy currents and the commutator is ready for the coil connections.

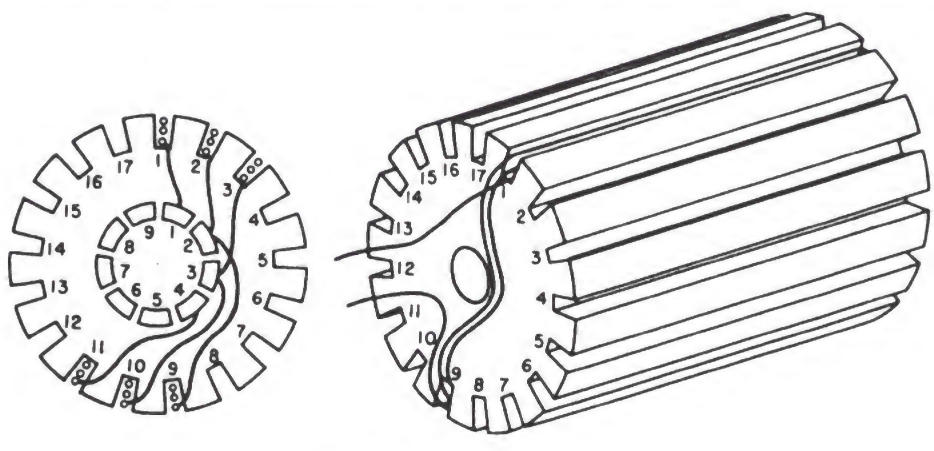


Figure 30.—Drum core.

COIL SPAN

But before you put any complete windings on this core, look at figure 31. It's a 32-slot core laid out flat to show the connections. And for each different field, one coil is set in its

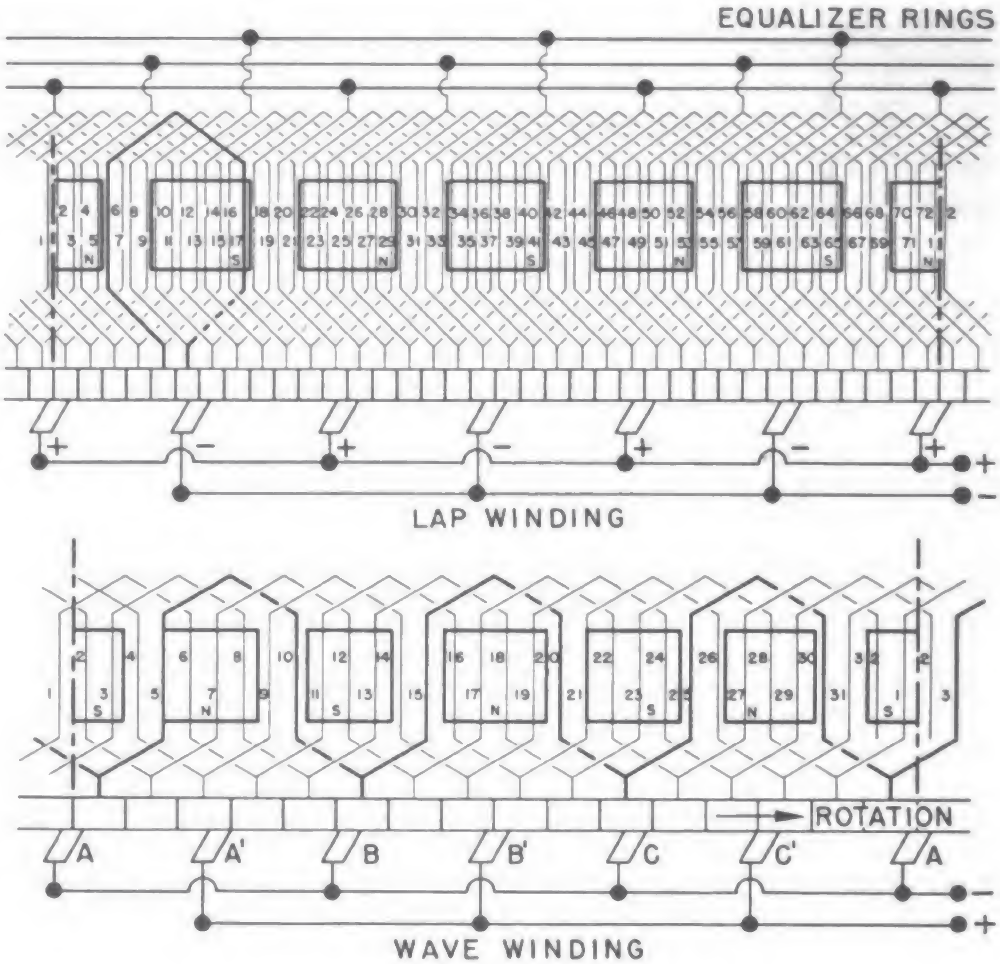


Figure 31.—Armature coil spacing.

correct position. In the lap winding, the coil sides are in slots 6 and 17. In the wave winding, the coil sides are in slots 5 and 10. What's the connection between the poles and the slots holding the coil? Just this—the COIL SIDES in each case are separated from each other by about the SAME DISTANCE that separates the centers of the FIELD POLES. Whenever these two distances are equal, as in the wave winding (5 to 10 and 7 to 12), the COIL SPAN IS FULL POLE PITCH. Whenever the coil sides are separated by a fraction of the distance between field poles, (6 to 17 and 10 to 22 in the lap winding), the coil span is FRACTIONAL PITCH.

The principle of pitch windings is important. It means that all coil sides, in any winding, are separated by about the same distance that separates the field poles.

Now glance back at figure 31 and you'll see WHY windings have approximately full pole pitch. Notice in all the drawings that whenever one coil side is under the middle of a north pole—the other side is under the middle of a south pole. Both sides of the coil are cutting maximum flux at the same instant. And when one side is in the neutral plane so is the other side. When one side is not cutting flux, neither is the other. In any position of the rotating armature, both coil sides get the same treatment from the field flux.

Now, when both sides are under the middle of their poles, their induced voltage is high. And it ADDS! Use your generator hand rule to prove that the induced voltage is additive. You'll find that you go right around the coil WITH the voltage arrows. AND when both sides are in the neutral plane, their induced voltage is zero.

Here is the whole story—when the coil pitch is about full (9/10ths is O. K.), the induced voltages will add from side to side, and the whole coil's voltage will go to zero when both sides are in the neutral plane.

In both lap and wave winding, coil span is about full pitch.

LAP WINDING

The coils for a modern armature are FORM WOUND. That is, the wire or copper bars are shaped over a wooden form or bent in a press to fit their armature core. Figure 32 shows

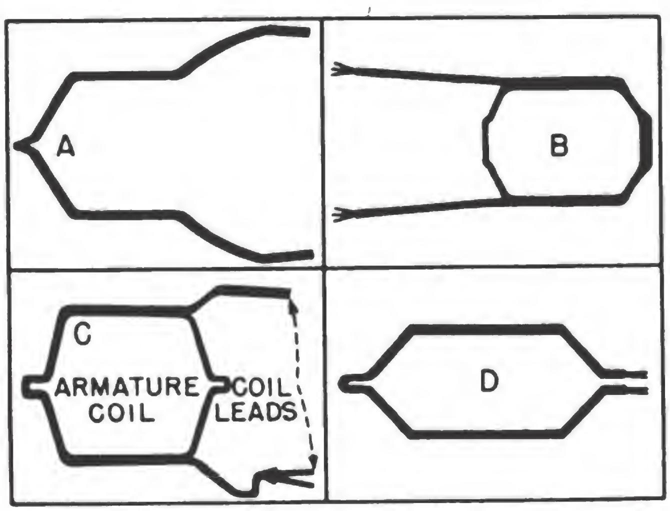


Figure 32.—Formed armature coils.

four different form wound coils. It shows that each coil may be made up of one, two, or more separate conductors. But regardless of how many conductors make up the coil, they're all wrapped together in a common insulator sheath. And each coil has only two leads for connecting to the commutator.

In making form wound coils, the two coil sides are exactly as far apart as the coil span. Also, the back of the coil is long enough to reach between the two slots in the core which hold the sides. And the leads are long enough to run from the slots to the commutator risers. You'll notice every one of these points in the coils of figure 32.

Now you have the principles of ANY armature winding—coils set on the core at just about full pole pitch—one, two, or more, conductors bound together to make up a coil—all conductors of one coil connected so that only two leads are led out for commutator connection.

Now, go on with the LAP WINDING—

The lap winding gets its name from the appearance of its winding diagram. You'll see that the coils seem to "lap-over" each other as they're placed on the core. Figure 33 shows the

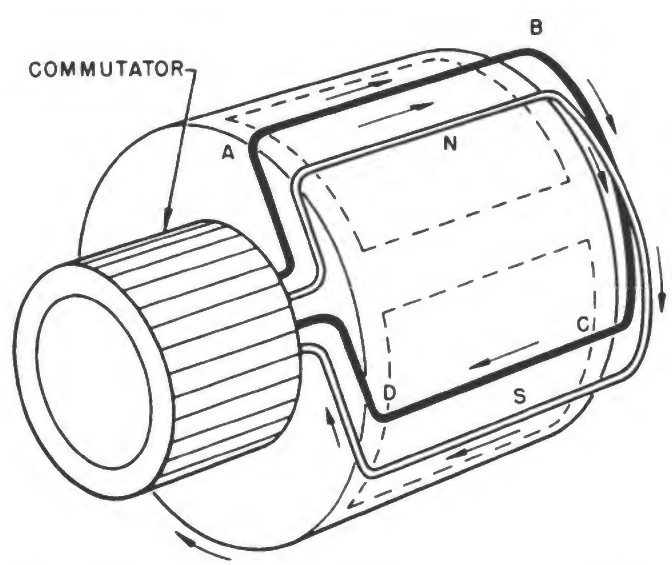


Figure 33.—Two coils of a four pole lap winding.

beginning of the simplest lap winding. See how the white coil laps over the black, and how each coil span is nearly full pole pitch. No matter how complicated the winding gets—you can

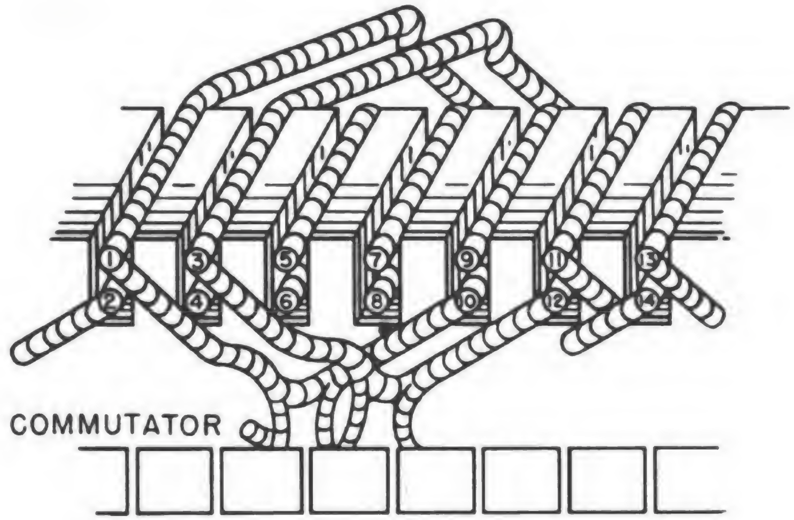


Figure 34.—Simplex lap winding.

be sure that this lapping continues all the way around the armature. Figure 34 shows a section of the completely wound armature of figure 33.

Figure 35 is a drawing of a four pole lap winding. There are THREE things you should get out of this drawing—

FIRST—there are two coil sides in each slot. These are numbered with the ODD numbers on TOP and the EVEN numbers on the BOTTOM. Coil sides numbered like this are called WINDING ELEMENTS. Trace from 1 to 10—this is one coil. It has

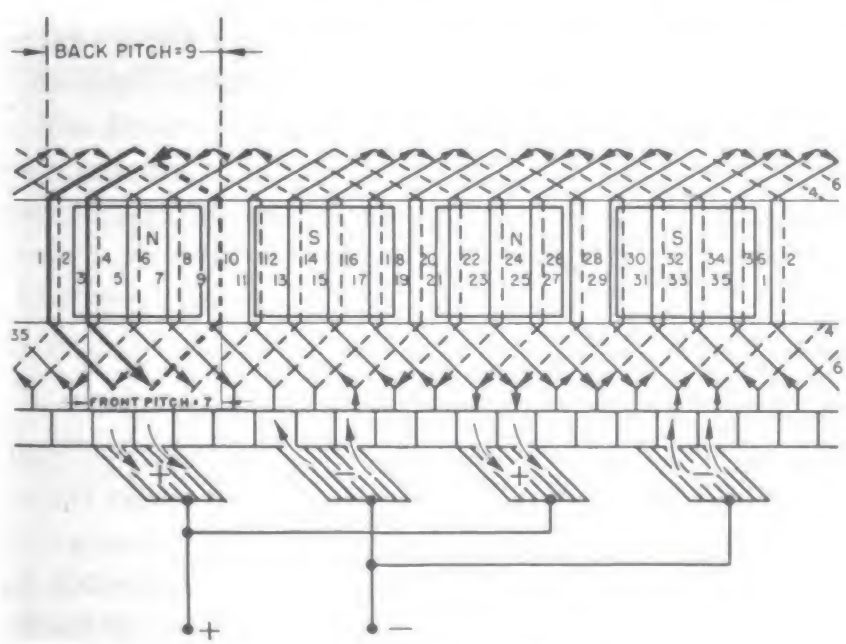


Figure 35.—Four pole lap winding.

one side (1) in the top of the slot and the other side (10) in the bottom of the slot. This TOP TO BOTTOM ARRANGEMENT HOLDS TRUE FOR ALL WINDINGS.

SECOND—the distance between the back ends of the winding elements (coil sides) is called the BACK PITCH (Y_b). It is measured in the number of winding elements spanned at the back. The back pitch of this winding is 9 ($Y_b = 9$)— from 1 to 10 is 9. A back pitch of 9 simply means that 9 winding elements are between the two coil sides. Notice that back pitch is determined by coil span. But coil span is measured in terms of pole pitch (the distance IN SLOTS between field poles). And back pitch is measured in terms of the number of WINDING ELEMENTS between the two coil sides. If $Y_b = 13$., then the two coil sides would be the winding elements numbered 1 and 14, or 3 and 16, or 11 and 24, or any two elements that are 13 numbers apart.

THIRD—the distance between the front ends of the winding elements is called FRONT PITCH (Y_f). In figure 35, the front pitch is 7 ($Y_f = 7$). Yes 7! Here's how you get it—elements 10 and 3 are both connected to the commutator segment marked X. Therefore 3 and 10 are connected together. The distance between the coil sides is the front pitch, and from 10 to 3 there are 7 winding elements spanned.

You're probably saying, "Sure, but 10 and 1 are connected also." That's right, they are. But you get the power off the commutator. If 10 and 3 weren't connected together at the segment your power would just circulate around and around the coil and never be delivered to the brush. So you are principally concerned with the coil's connection at the commutator. This is given by the Y_f.

CONNECTIONS

Why are you running a generator? To get as much voltage as possible out of it—right? You know how to make the voltages of a number of coils ADD. Connect them in SERIES! And in order to do that, your Y_b and Y_f must be DIFFERENT. Look at figure 35. Here's the complete winding diagram for the two sections you've already seen in figures 33 and 34. Pretty com-

plicated isn't it? Well, it won't be if you go through it piece by piece. It's just an armature split down one side and laid out flat. If you took the page and curled it up into a cylinder, you'd have the armature again.

Looking at the front and back pitches first. They're different and that makes the elements a series connection. The elements, by being in series, produce ADDING voltages. You can prove this by tracing the current through each successive element.

Let's assume that a N field pole induces an emf toward the bottom of the page. Then an S pole will induce emf toward the top. Starting at element 5 (it's best to start here because 5 is in the middle of the pole), emf is induced DOWN. Current is forced into commutator segment 5. And right out again to element 12 ($Y_f = 7$). Element 12 is under a S pole, so induced emf is UP. Notice that emf's of 5 and 12 add. Current is forced from 12 to 3 ($Y_b = 9$)—where it picks up more emf. Element 3 is connected to segment 4, so current, backed by the added emf's of elements 5, 12, and 3 is forced into this segment. At this point current can go two ways—either up to element 10 ($Y_f = 7$) OR out on the brush. Which? Out on the brush, because element 10 is moving under the N pole and also gives 10 an induced emf DOWN. The two emf's (elements 3 and 10—both down) force the current into the segment and then into the brush. You've got power off the armature and into the load circuit. And that power has a total voltage equal to the sum of the induced emf's of a number of elements.

Trace the return circuit from the load. Start at the positive brush nearest the left hand side. Current flows into segment 8. From segment 8 to element 18, to element 9 ($Y_b = 9$), to 16 ($Y_f = 7$) via segment 7, and so on. You can trace it through. You'll find that the current finally is delivered to the brush at segment 4. And this current has been through elements 18, 9, 16, 7, 14, 5, 12, and 3 BEFORE being delivered to the brush. In short IT HAS PICKED UP VOLTAGE IN EVERY ONE OF THESE ELEMENTS—EIGHT OF THEM—BEFORE BEING DELIVERED TO THE BRUSH.

There are similar paths between any positive and negative brush. And this will tell you HOW MANY paths—each segment has two elements connected. Therefore, from brush, to seg-

ment, to elements, there are two paths for current PER BRUSH. With TWO positive brushes, current is coming into the windings via FOUR paths—With TWO negative brushes, current is leaving the windings via FOUR paths. It's a FOUR PARALLEL circuit. Which means that any given element carries only one-quarter of the total load current. This is a good thing to remember. For heavy current loads, use a lap winding. Each conductor carries less current because a lap winding has many paths through the armature. In fact, a simplex lap winding has as many paths as the field has poles.

SUMMARY OF LAP WINDING

For a lap winding to be "right" it must have—

FIRST—the coil span must approach or be equal to the pole pitch. This insures opposite sides of the coils being under opposite poles, which is necessary so that voltages WILL ADD. It's better to have the span a LITTLE LESS than full pitch (fractional pitch). Fractional pitch provides better commutation with less arcing.

SECOND—the winding connections (between the elements—at the back and at the commutator) must include each element ONCE and ONLY ONCE. This insures a balanced voltage in all the paths. A balanced voltage is provided by always making the Y_f and Y_b odd numbers. Odd-numbered pitches mean connecting top elements to bottom elements.

THIRD—the winding must be REENTRANTS, or closed on itself. That is, the winding must be a complete circuit within the armature. This condition is obtained by making the Y_b and Y_f different. The STANDARD DIFFERENCE is 2. It might be 4 or 6 but it must be SMALL and it must be EVEN.

DESIGNING A LAP WINDING

You're not going to be an engineer or a designer of electrical machinery. BUT, you may have to rewind a burned-out armature. And it's a swell feeling to have it all back together and RUNNING without overheating and without sparking.

Here's a job for you. A four-pole generator armature must be rewound. It has 18 slots and is to have a two-layer simplex

lap winding. How many elements? That's simple—36. Because two elements (from TWO-layer) multiplied by 18 slots equals 36 elements. The coil span is 18 slots divided by 4 poles. No, not 4½. Ever see a coil side in an armature halfway between two slots? The coil span would be 4 slots, which makes it a fractional pitch winding. The back pitch should be as close to 36 (elements) divided by 4 (poles) as possible (and still be odd). $36 \div 4$ equals 9. $Y_b = 9$ (perfect). The front pitch must be different from the Y_b by 2. Make $Y_f = 7$. Now make up a winding table. Start at element 1. Below is the winding table completed for you.

1-10—3-12—5-14—7-16—9-18-11-20-13-
22-15-24-17-26-19-28-21-30-23-32-25-
34-27-36-29—2-31—4-33—6-35—8—1-

It shows every connection necessary on the armature. Take element 25—it's in the 13th slot $(\frac{25}{2} = 12\frac{1}{2})$; it's connected in the back to element 34 (slot 17) because $Y_b = 9$; and it's connected in the front through the commutator segment to element 32 (slot 16) because $Y_f = 7$. Follow the connections for any element. You can find its slot and both its front and back connection. Would you like to see the completed winding diagram? Go back to figure 35. It's the same armature you've been studying.

One thing has been omitted. That's the commutator pitch, Y_c. In a simplex lap winding, Y_c is always equal to 1. That means that each successive front connection is made through ADJACENT segments. Distance (or pitch) is one. You'll see later that duplex and triplex windings change Y_c.

WAVE WINDINGS

WAVE WINDINGS are fairly easy, IF you've got lap winding down pat. In fact, the wave winding uses exactly the same principles as the lap winding. The only difference between lap and wave windings is the method used to connect the winding elements.

Compare the two drawings in figure 36. *A* is a lap winding and *B* is a wave winding. Notice that the coil side AB corresponds in the two drawings. In both cases AB is connected to the coil side CD, which is under the next pole. In the LAP winding, C is connected BACK to EF, which is under the SAME pole as

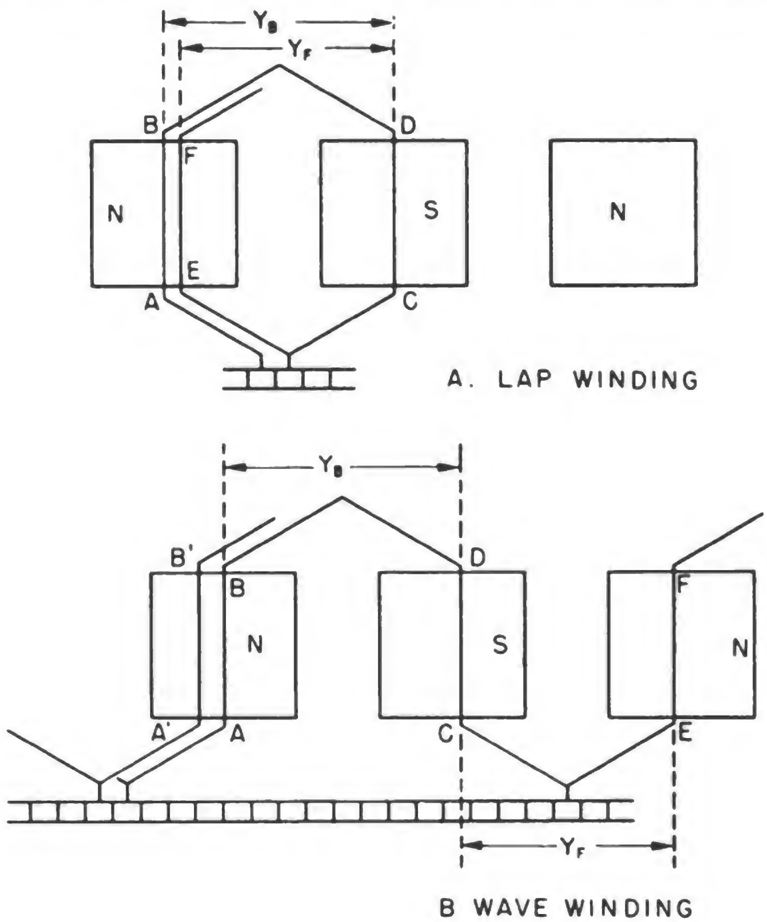


Figure 36.—Lap and wave windings.

AB. But in the WAVE winding, C is connected FORWARD to EF, which is under a pole two poles away from AB.

This is the essential difference. In lap windings the connections are made BACKWARD—lapping over each time. In wave winding the connections are made FORWARD, so that the winding passes under EVERY field pole before it returns to the first pole. Notice that Y_b and Y_f mean the same thing in both windings. Also, that the coil span is about full pole pitch in both windings.

The worst thing that can happen to a wave winding is to have it close on itself after one passage around the armature.

This means that, in figure 36, the winding would reconnect to AB after passing under every pole. The result would be a voltage produced by only one winding—four winding elements.

In wave winding, Y_b and Y_f must be odd. Then the top-bottom arrangement of coils is assured. But Y_b and Y_f do NOT have to be different. They can be the same or different, but the AVERAGE pitch, Y, must be watched. Y must NEVER be equal to the total number of elements (Z) divided by the number of poles (P).

Here's what would happen if Y was exactly equal to Z divided by P. Imagine a 16-slot armature with a two-layer wave winding. If Z is divided by P, $32 \div 4$, the Y is 8. And the winding table for the first five elements is $1 - 9 - 17 - 25 - 33$ (or 1). See what happens? You pile right up in the same slot you started from. This winding closes on itself after one passage. Instead, use this formula to find average pitch—

$$Y = \frac{Z + 2}{P} = \frac{32 + 2}{4}$$

Now the average pitch is 7½ or 8½. Adding 7½ and 8½, you get 16. Since Y_b and Y_f must be whole numbers and odd, either 9 and 7 or 7 and 9 would be good values of Y_b and Y_f. Of course the total of Y_b and Y_f divided by two must equal the average pitch, Y.

Figure 37 shows a 17-slot armature wound as a four-pole, two-layer simplex wave winding. Start at element 1 and trace a complete circuit around the armature. The winding table starts out—

$$Y_b = 9$$
$$Y_f = 7$$
$$1–10–17–26–33–8–15$$

Notice that your Y_b and Y_f tell you where to place the coils and where to connect them.

The heavy circuit in figure 37 shows ONE path between the positive and negative brushes. The light circuit shows the other path. And there are ONLY TWO paths in a simplex wave winding regardless of the number of poles. This means that each element carries one-half the total load current AND the

current MUST PASS THROUGH ONE-HALF THE ELEMENTS between brushes. This gives you a higher voltage than the lap winding, but a lower current carrying capacity.

In the lap winding one brush was needed for every path. But in the wave winding, you can get along with ONLY TWO BRUSHES.

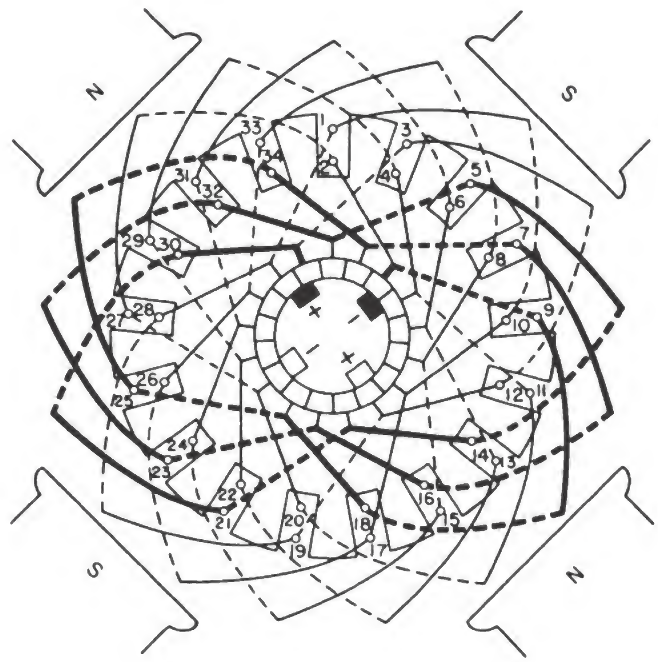


Figure 37.—Simplex wave winding.

The number of poles doesn't make any difference in a wave winding. Two brushes will do the job because there are only two paths. You can check this in figure 37. Imagine that the two lower brushes are gone. You can still trace from the positive to the negative brushes THROUGH THE ARMATURE. And you'll pass through EVERY ELEMENT. This proves that no VOLTAGE would be lost by removing two brushes. BUT for any given load the remaining two brushes would have to carry twice as much current. For example, say that the armature of figure 37 has a 20 ampere load at 220 volts. Each set of two brushes is carrying 10 amperes at 220 volts. But, if you remove one set of brushes, the remaining set must carry 20 amperes at 220 volts. This would do no damage, IF the brushes were large enough. But in this particular armature, designed for four brushes, 20 amperes would overload the brushes. Arcing

(sparking) would result and the commutator would be pitted and burned.

In a wave winding, the number of commutator segments must be equal to the number of elements divided by 2. How to get the commutator pitch (Y_c)? Divide the number of segments by the number of pairs of poles. In figure 37 this would be $17 \div 2$, or $8\frac{1}{2}$. Obviously, Y_c cannot be a fraction, so the nearest whole number becomes Y_c. In this case $Y_c = 8$. Remember trying to wind a 16-slot, 32-element, armature a few pages back? In that armature the Y_c would have been an even 8, by dividing 16 by 2. This gives you a rule—anytime the number of segments divided by the number of poles gives you whole number for Y_c, or, anytime the average pitch is a whole number, the armature CANNOT be wound as a wave winding. You need an armature with an odd number of slots and segments for wave winding.

DUMMIES

Well, what would you do if you HAD to wave wind an armature with an even number of slots? You make it UNEVEN by putting in a DUMMY COIL. Figure 38 shows a dummy coil set in a wave winding. All a dummy coil does is take up space (like

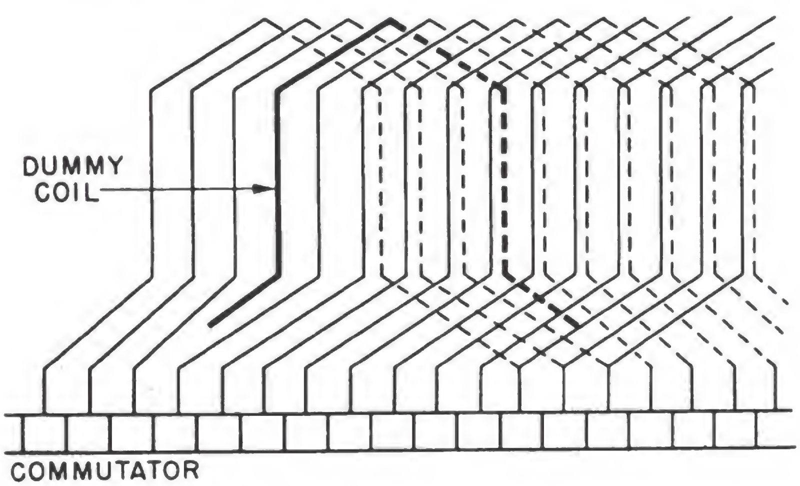


Figure 38.—Dummy coil.

other dummies)—its two leads are taped and insulated from the other windings. The only reason for a dummy coil is to balance the armature. If you left the two elements of the dummy

coil out of their slots, those slots would be lighter in weight. And the armature would vibrate because of the unequal distribution of weight.

By eliminating the two elements of the dummy coil in your connections, you make the winding "creep." That is, it does not close on itself after one passage around the armature. Instead it creeps two elements beyond the starting point for each complete passage around the armature. This is called a FORCED winding.

MULTIPLEX WINDING

What is the difference between a 10 k.w.-115 volt generator and a 50 k.w.-115 volt generator? All right—one is bigger than the other! But how do they differ inside? How are their WINDINGS different?

Let's settle the "115 VOLT" part first. In order to produce 115 volts, there must be a certain number of conductors cutting flux and connected in series between sets of brushes. Say that this number is 90 conductors. In a 4-pole, 18-slot, 36-element, simplex lap job, there are 9 elements in each path between brushes. That means that there MUST be 10 conductors in each element ($90 \div 9 = 10$). That's the only way to get 90 conductors on the armature between sets of brushes. In a 4-pole, 17-slot, 34-element, simplex wave job there are 17 elements between brushes. Remember—only two paths in a wave winding. This means that each element MUST contain $90 \div 17$, or 5 or 6 conductors. You can see that THE VOLTAGE PRODUCED IN ANY GENERATOR is determined by the NUMBER OF CONDUCTORS PER ELEMENT. Or say the NUMBER OF TURNS PER COIL. The size of the generator (10 k.w. or 50 k.w.) has nothing to do with the number of turns per coil. Only the VOLTAGE is connected with TURNS PER COIL. That settles the "115 volt" part.

Now for the k.w. ratings—10 k.w. and 50 k. w. The k.w. rating tells you how much current the generator can deliver at the rated voltage. The 10 k.w. job can deliver—

$$I = \frac{P}{E} = \frac{10{,}000}{115} = 87 \text{ amp.}$$

and the 50 k.w. job can deliver—

$$I = \frac{P}{E} = \frac{50{,}000}{115} = 435 \text{ amp.}$$

In short, the 50 k.w. job delivers 5 times as much current as the 10 k.w. job. And you know what that means—larger CONDUCTORS or MORE CONDUCTORS IN PARALLEL. If LARGER CONDUCTORS are used, it's simple. Windings are connected the same in both jobs. The only difference is in the size of the current carrying parts—coil conductors, leads, commutator segments, brushes, and pigtails—they are all about 5 times larger in the 50 k.w. job.

But if more conductors in parallel are used—it's not so simple. More conductors in parallel are put on the armature by adding one, two, or more PARALLEL WINDINGS. If just ONE winding is used (the kind you've learned about so far), the winding is

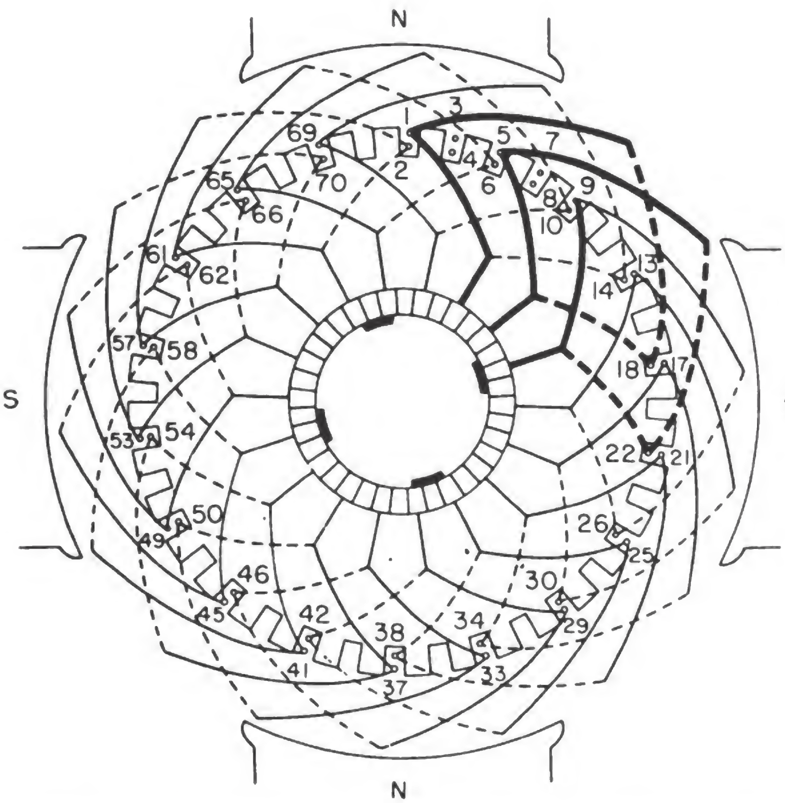


Figure 39.—Duplex-double reentrant, one winding only.

SIMPLEX. If two windings are used it's called DUPLEX. If three windings are used it's called TRIPLEX. And so on, with the

general term MULTIPLEX applied to all windings other than simplex.

Let's take the DUPLEX LAP first (figure 39). It's a 4-pole, 36-slot, 72-element, duplex lap job—but only one winding is shown. $Y_b = 17$ and $Y_f = 13$. Follow this one winding through. You'll notice that making a difference of 4 between Y_b and Y_f leaves every other slot empty. These empty slots will receive the second winding. Likewise, every other commutator segment is skipped. This leaves room to connect the second winding to the commutator. Y_c in a duplex lap winding is always 2.

Just like a simplex job, the winding is reentrant. Follow it around the whole armature, and notice that element 14 is connected to element 1—thus closing the winding on itself. This first winding of a duplex job is exactly like an 18-slot, 36-element simplex winding. If it were put in a generator, it would work fine, except that the current carrying capacity would be limited by the size of the conductors in the one winding.

Now, to make it a duplex, just set in another simplex winding in the empty slots. Y_b, Y_f, and Y_c are exactly the same as the first winding. The two windings are entirely separate—they're insulated from each other.

This is called a DOUBLE REENTRANT DUPLEX WINDING. "Double reentrant," because both windings close on themselves. And "duplex," because the windings form two parallel paths around the armature.

TRIPLEX or QUADRUPLE windings merely have THREE or FOUR separate windings on the armature. You can always spot the complexity of a winding by the commutator pitch. In simplex, $Y_c = 1$; in duplex, $Y_c = 2$; in triplex, $Y_c = 3$; and so on.

It's about time for "Where were we?" on the difference between a 10 k.w. and a 50 k.w. generator. Look at figure 40—it compares the current paths for the 50 k.w. job wound as a simplex, duplex, or triplex armature. In the simplex winding, the whole 435 amperes comes from one winding through one segment. In the duplex winding, half the 435 amperes comes from each winding. And in the triplex winding, only one third the 435 amperes comes from each winding. Which one is best? The triplex—because the load is distributed over three windings. And that makes for smaller wire and less heat.

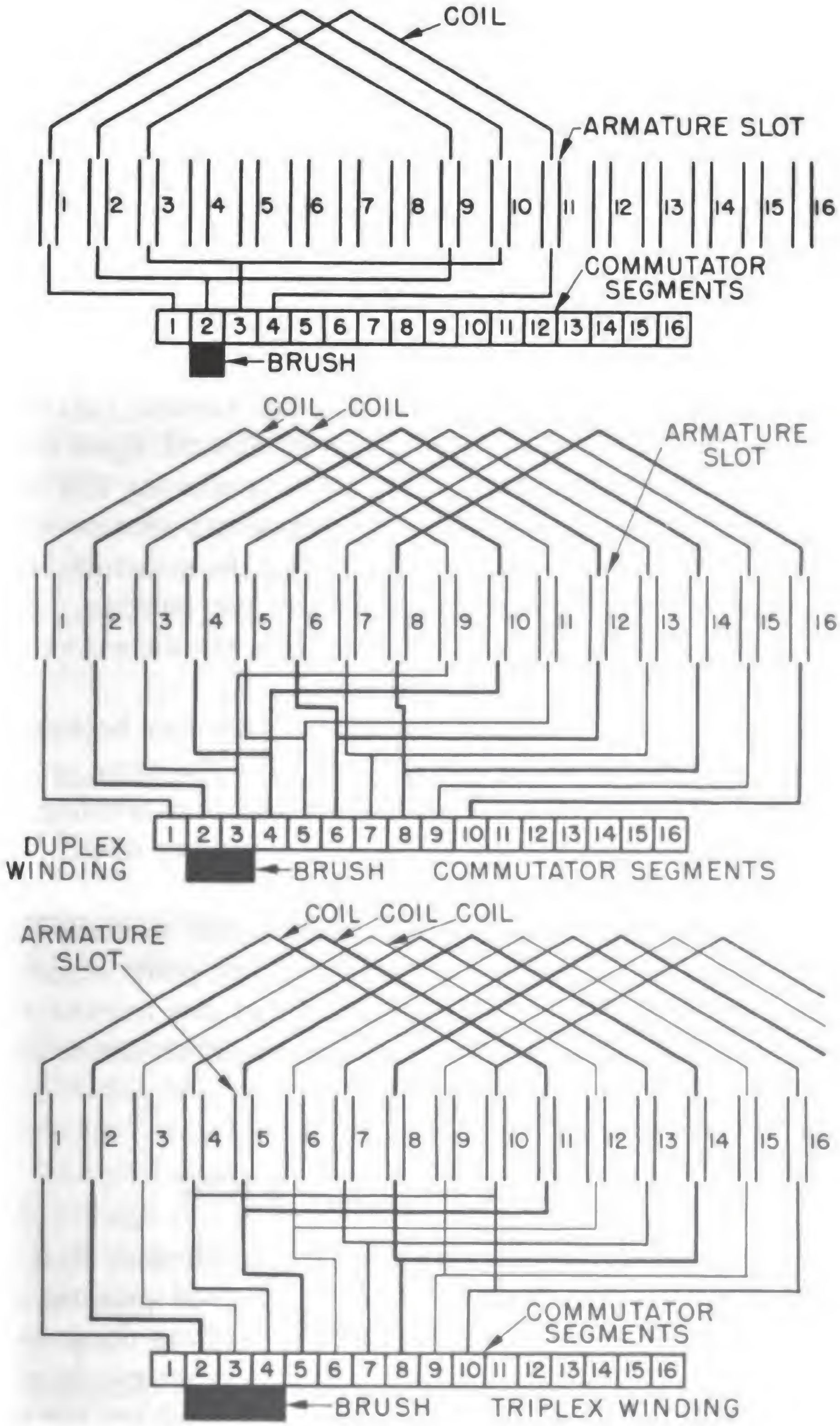


Figure 40.—Winding loads in simplex, duplex, and triplex windings.

Notice in figure 40 how the brushes change size. In the simplex, the brush is the width of one segment and contacts two segments. In the duplex, the brush picks up current from two segments (two windings), so it must span two segments. And in the triplex, three windings are furnishing current, so the brush must span three segments. That's another easy way to spot a simplex, duplex, or triplex winding—by the width of the brushes.

You may run into a duplex winding that is SINGLE REENTRANT instead of double reentrant. This happens when there is an odd number of slots. The first winding cannot close on itself the first time around the armature. The last element falls in the slot next to where it began. It has to go around again before closing. But in going around again, the first winding fills in the second winding's slots. In fact IT BECOMES THE SECOND WINDING. At the finish of the second trip around the armature, it will connect to the first element thus closing the winding. Since this winding is closed only once it is called a SINGLE REENTRANT DUPLEX WINDING.

And wave windings, too? Absolutely—they can be simplex, duplex, or triplex just like the lap jobs. It's the same process. For a duplex wave, you simply put on the first winding, adjusting your Y_b and Y_f to leave every other slot open. Then the second winding fills in these open slots.

You remember that a simplex lap winding had as many paths as poles. And the simplex wave had only two paths regardless of the number of poles. Now, making either one DUPLEX DOUBLES THE NUMBER OF PATHS. And making either one TRIPLEX TRIPLES THE NUMBER OF PATHS.

CONFUSION OR GOOD SENSE?

What's the sense to all these different windings? It is not just to confuse you. Each winding has a good purpose, and here are three principles which determine winding design—

ONE—SERIES CONNECTIONS. Windings in series—by wave or by many turns per coil—give you a high voltage but generally a lower current capacity.

TWO—PARALLEL CONNECTIONS. Windings in parallel—by lap, by many poles in lap, or by duplex or triplex in both

wave and lap—give you many paths on the armature. This means a higher current capacity, but a lower voltage.

THREE—LOAD REQUIREMENTS. Load requirements—high voltage or heavy current—vary from load to load. The generator supplying the load is built to deliver high voltage or heavy current—whichever is required.

Let's take a generator and fit it for SIX DIFFERENT JOBS by just CHANGING THE WINDING CONNECTIONS. It delivers 120 amperes at 300 volts in its original connections as a 6-pole, simplex lap. The accompanying table shows what you can do by merely changing the winding connections.

Connections	Paths	Volts	Amperes	Power (k.w.)
Simplex lap............	6	300	120	36
Duplex lap.............	12	150	240	36
Triplex lap............	18	100	360	36
Simplex wave..........	2	900	40	36
Duplex wave...........	4	450	80	36
Triplex wave...........	6	300	120	36

Pretty good, eh? Six different values of current and voltage simply by changing the design. In the table two things stand out—

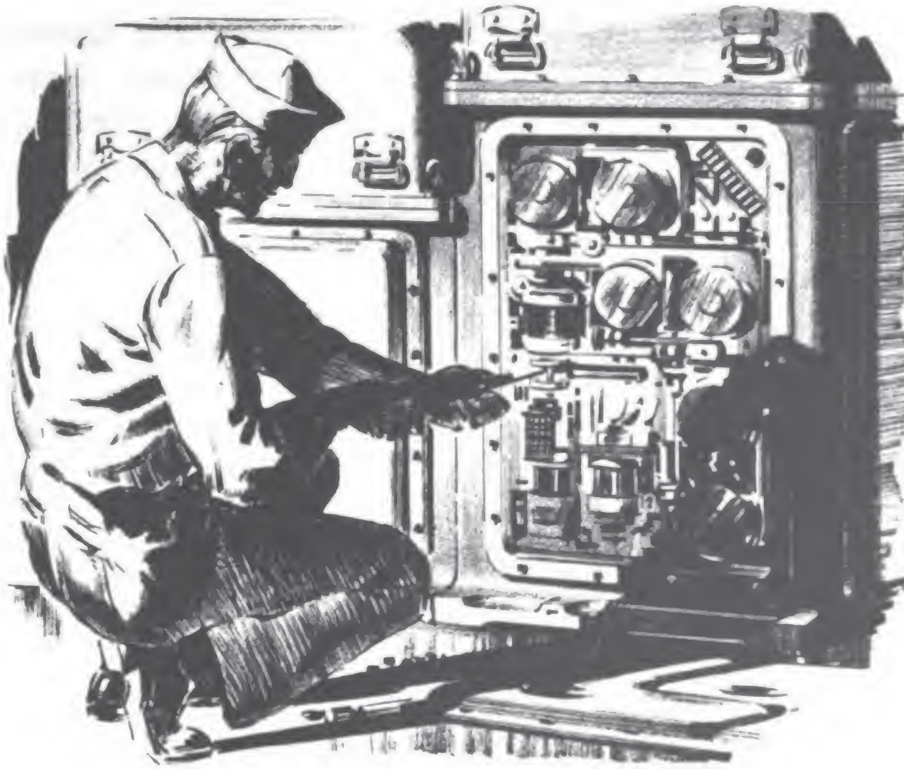
Every time you increase the number of paths, the CURRENT INCREASES and the VOLTAGE DECREASES. And the increase or decrease is exactly in proportion to the change in paths.

The power is constant—because the current increases and the voltage decreases by EXACTLY THE SAME RATIO.

To go back to the 10 k.w. and 50 k.w. generators. If the 10 k.w. machine is simplex wave wound, how could you design the 50 k.w. job so that it would use the SAME SIZE WIRE?

The voltages are the same, and the current ratio is 5 to 1. So the first job is to put 5 times as many paths in the 50 k.w. generator. Looking at the table on this page, you find that no combination gives you a 5 to 1 ratio. But it would be O.K. to use 6 to 1—this would give you a little more current than the

rating indicates. You'd select the duplex lap winding (12:2 = 6:1). But this is not the whole job—because when you increase the number of paths by six times, you cut to one-sixth the number of conductors in series. You have the carrying capacity for 435 amperes all right, but the voltage is cut down to one-sixth of 115 volts. The only way to get this voltage back up to 115 volts is to increase the number of slots by six times. And put six times as many conductors in every path. Increase the size of the machine? Sure—but you expect that when you go from a 10 k.w. to a 50 k.w. generator.



CHAPTER 5

GENERATOR—COMMUTATION

THE ESSENTIALS

So far you've been given a good picture of the two essential parts of a generator—the ARMATURE and the FIELD, and from your 3c work, you know the relationship of the armature to the field. These essential parts make up the whole machine in small generators but not in larger installations. When you start studying the bigger machines, you'll find many special parts added to the essentials and performing special jobs.

WHY THE ADDITIONS?

Remember the old model T? It ran all right, but newer models run a lot smoother with more power, and they can stop on a dime. What's the difference between the two cars?
ıal parts—IMPR

Likewise, improvements make a generator more serviceable and efficient. The older models were just an armature and a field. They were plenty rough! You couldn't keep them on a rated voltage. And they burned up commutators regularly. Your modern machines are built to deliver steady, rated voltage and they're a lot easier on commutators. The reason for better operation is in the improvements added to the modern machine.

COMMUTATION

COMMUTATION is a good-sized word, and it covers a good-sized field of action. Understanding commutation is a lot easier

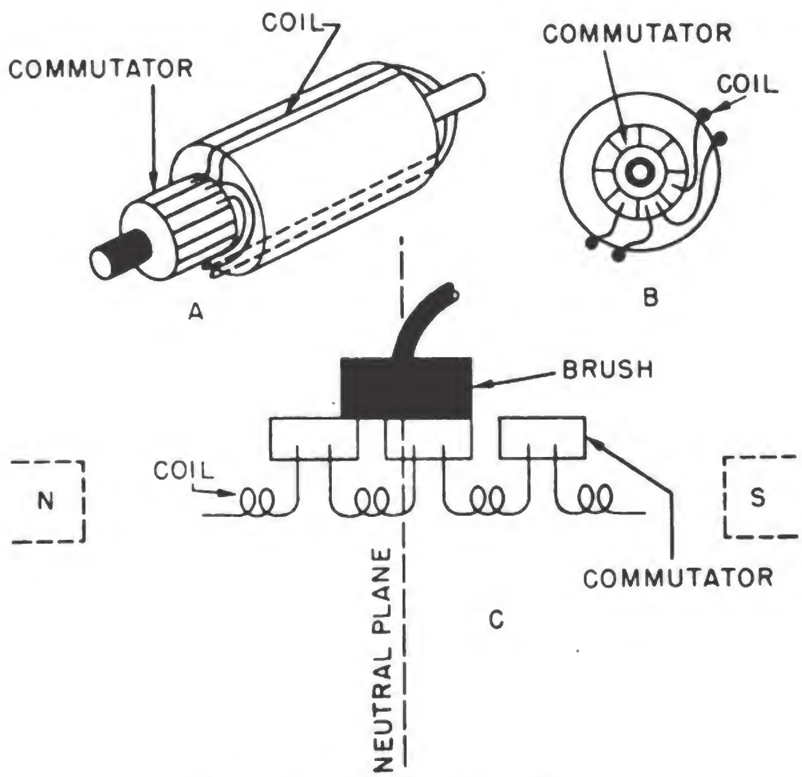


Figure 41.—Commutation diagram.

if you split the process into two divisions—IDEAL and PRACTICAL. Ideal commutation describes what SHOULD happen. And practical commutation describes what DOES happen. And you'll find there's a big difference!

First, see what SHOULD happen. Figure 41 shows three views of an armature. *A* is the side view, *B* the end view, and *C* is the schematic of the commutator brush coils, or winding

elements. Drawing *C* illustrates the type of schematic always used to explain commutation—you'll see a lot of them.

The coil selected in drawing *A* is also indicated in the other diagrams. Notice how much easier the positions and commutator connections of the coils can be studied when you use a diagram like drawing *C*. Think of the coil as being fitted into the armature grooves, instead of being flat. If you have trouble visualizing this schematic, make a cylinder by rolling the page with figure 41. Notice how the commutator becomes round and how the coils fit the rounded armature.

What kind of winding is this?

The coil span covers about one-half the armature—so it must be a two-pole job, and the commutator pitch is ONE. This also tells you it must be SIMPLEX LAP—meaning TWO PATHS for current to travel, one on either side of the armature.

Now to complete the picture of commutation—add the pole pieces, a north pole on the left-hand side and a south pole on the right-hand side. That puts the neutral plane (where no emf is induced), equidistant between the pole pieces, with the brush straddling the neutral plane. The coils on the left side are under a north pole, while those on the right side are under a south pole. That means you will have oppositely induced voltages on the two sides of the neutral plane. One more important fact to remember—the COILS CONNECTED TO THE BRUSHES are in the NEUTRAL PLANE, and therefore they have NO induced voltage.

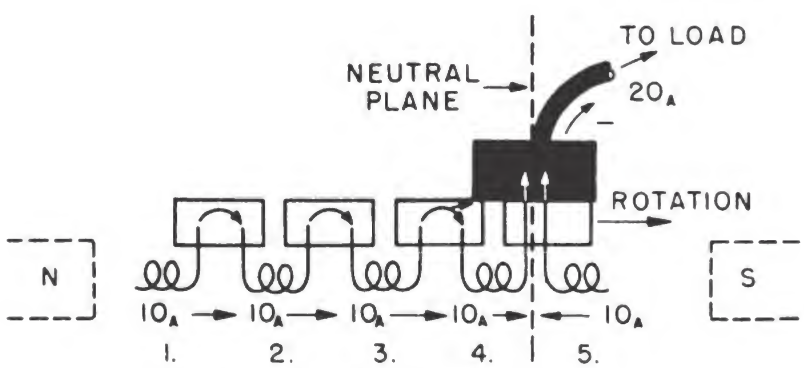


Figure 42.—Ideal commutation—No. 1.

Figure 42 is your complete picture. But here's one idea you ... the coils and com...

grams show these parts standing still, but don't forget that each segment regularly moves out from under the brush.

Notice the ARROWS in the commutator in figure 42. They show the CURRENT DIRECTION through the coils, the segments, and the brush.

The ARMATURE COILS are indicated as moving to the RIGHT. This produces the same effect as having the BRUSH move LEFT, so in figures 42 through 46 the movement of the armature is indicated by moving the BRUSH to the LEFT.

Stop a minute now and look at figure 42. Ten amperes of current are coming up each side of the armature. Each of these currents is backed by the voltage of the generator—say 115 volts. At the neutral plane, both currents—10 amperes from each side—flow into segment 5. That makes the load current of 20 amperes, which the brush picks off the segment and delivers to the load. The 20 amperes, at 115 volts, circulates through the load and returns to the generator through the positive brush on the other side of the commutator. The 20 amperes re-enter the coils of the armature through the brush and commutator system. The process of re-entering the armature is part of commutation—it's the exact opposite of leaving. The 20 amperes split at the segment, 10 amperes going up either side of the armature.

Commutation is simply a repeat of this process over and over again. Out the negative brush and back in the positive—that's the whole story of commutation. Yes—the whole story AS LONG AS THE ARMATURE IS STANDING STILL. Which it is not!

You can't study the whole armature when it is moving because you can't keep track of every coil and every segment. But you CAN select ONE coil and follow it through the process. Then, since every coil is like every other coil, what you learn about one will be true for all the others.

COMMUTATION OF ONE COIL

Remember now—the coils are moving, and coil number 3 of figure 42 is the one you'll follow through. In this figure, it's under the north pole, carrying 10 amperes, and moving toward the neutral plane. An instant later it's in the position shown in [illegible] oil 3 now—the [illegible]

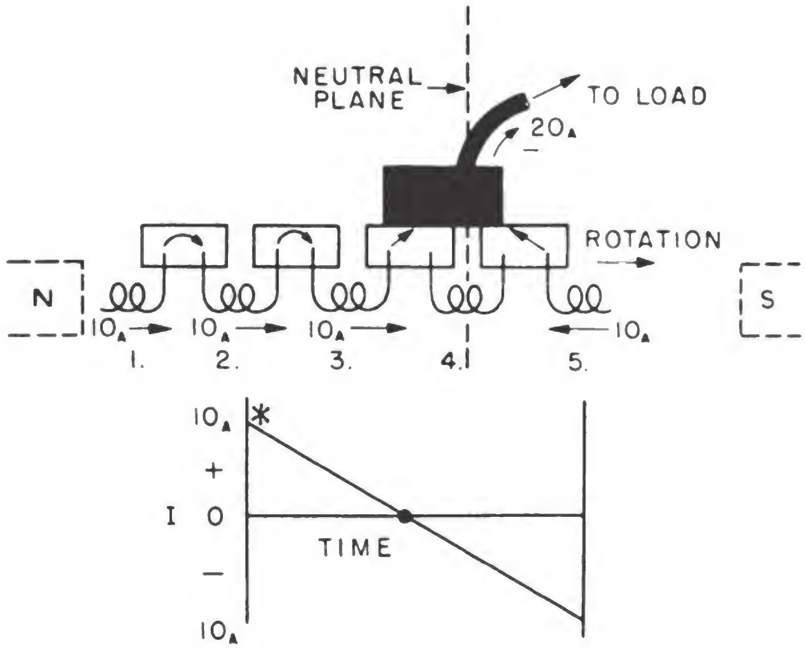


Figure 43.—Ideal commutation—No. 2.

THE BRUSH and not into coil 4. This is the true beginning of commutation—when the coil is connected to the brush.

Something else has been added in figure 43—a graph showing just what happens to the coil current during commutation. Try to connect the diagram and the graph together. The asterisk (*) over the graph shows the COIL CURRENT for the INSTANT

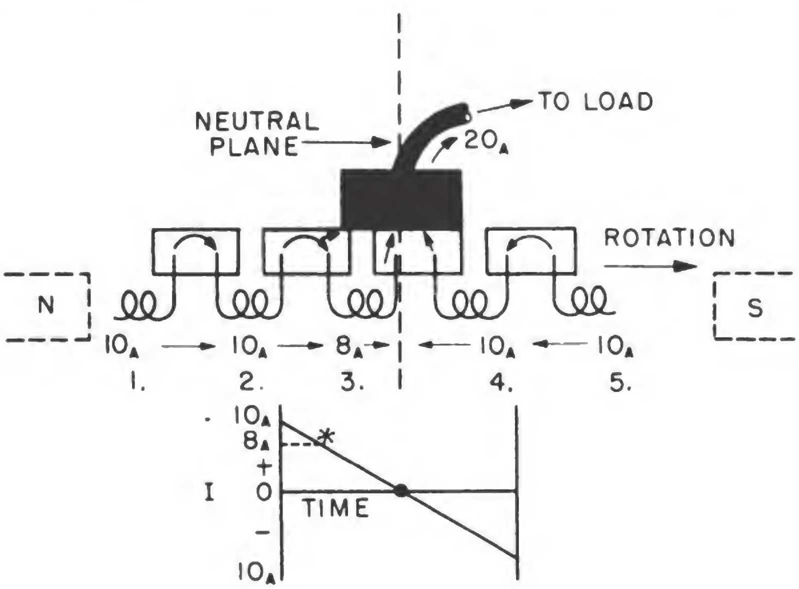


Figure 44.—Ideal commutation—No. 3.

of the DIAGRAM. Notice that the current in figure 43 is 10 amperes in the POSITIVE direction.

In figure 44, coil 3 has moved closer to the neutral plane. And here is where things start to happen. Coil 3 is no longer carrying a full 10 amperes. About two amperes from coil 2 are going directly to the brush. And that leaves only about eight amperes for coil 3 to carry. The graph shows the same thing. Coil 3 is moving INTO THE NEUTRAL PLANE, OUT OF THE LOAD CIRCUIT, and is also losing its current.

How about the generator's output? Does it decrease because coil 3 is losing current?

No, because coil 2 takes over the job that coil 3 is dropping. There are 10 amperes of current still coming up the left side—two amperes from coil 2 and eight amperes from coil 3. The amount CHANGES in individual coils, BUT THE BRUSH CURRENT REMAINS CONSTANT.

Now you're at the crucial point—when coil 3 reaches THE NEUTRAL PLANE (figure 45). Coil 3 is carrying NO CURRENT. How about the brush current? Steady at 20 amperes, because

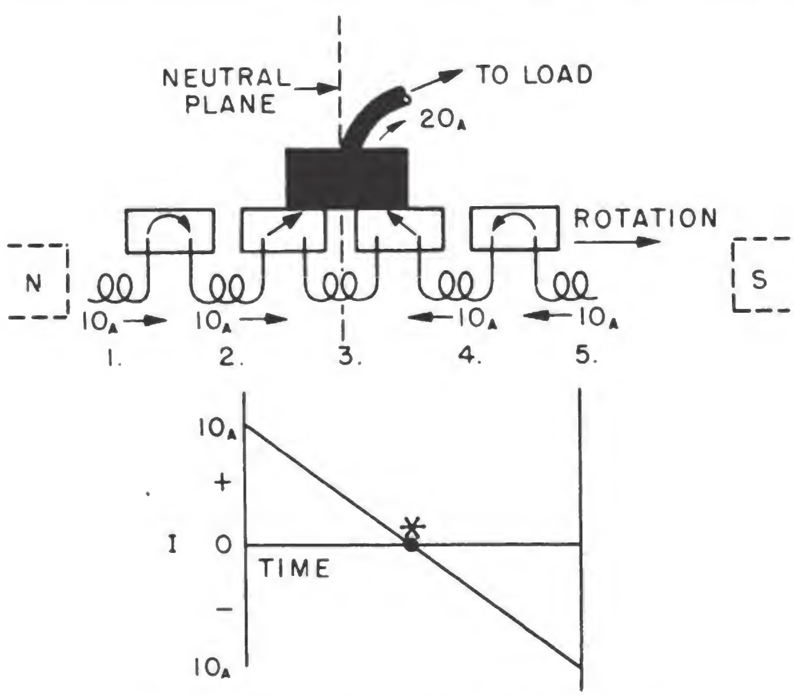


Figure 45.—Ideal commutation—No. 4.

coil 2 has taken over the job completely from coil 3. And this is what happens to EVERY COIL as it moves through the neutral plane—ITS CURRENT FALLS TO ZERO.

The final diagram for ideal commutation is shown in figure 46. Coil 3 has passed the neutral plane and is now under the SOUTH pole. The south pole flux induces an OPPOSITE voltage,

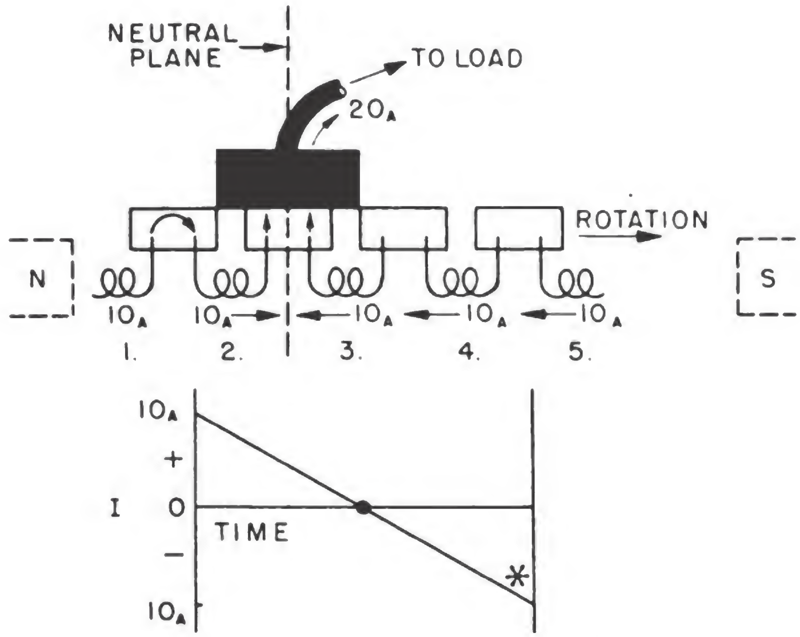


Figure 46.—Ideal commutation—No. 5.

and coil 3 is back at work—carrying current again, but in the REVERSE direction.

That is the commutation of one coil. In summary here is what happens, the coil moves out from under one pole, into the neutral plane, and then under the opposite pole. Current in the coil drops to zero in the neutral plane and then builds up again in the opposite direction. At the instant the coil current goes to zero, the brush short circuits the coil. But no damage results from this short, because the coil is without voltage while it's in the neutral plane.

It doesn't take much imagination to picture the results of IMPROPER commutation on the neutral plane. You'd have a coil with practically no resistance—perhaps 0.01 of an ohm. Just ONE VOLT across this circuit would WHAM 100 AMPERES through the coil, segments, and brush. It would make a good Fourth of July display, but would be pretty tough on the generator.

The process of IDEAL commutation is smooth. Each coil moves into position, connects to the brush, delivers current, passes

through the neutral plane, reverses its current, delivers current again, and finally passes down under the pole and away from the brush.

The total result of IDEAL commutation is a continuous and smooth flow of current to the load. But the continuous and smooth flow depends on three things—

There must be NO VOLTAGE in the short-circuited coil while the coil must be in the neutral plane.

There must be NO CURRENT in the short-circuited coil.

There must be NO SPARKING at the brushes.

TOO GOOD TO BE TRUE

Did you ever try to figure out how much a date was going to cost? How many times were you right? It's a good bet that you didn't guess right very often!

Ideal commutation is like that—it's too good to be true. It looks fine on paper, and it should work perfectly, but in practice it doesn't. There are two things that foul up perfect operation—SELF-INDUCTION and ARMATURE REACTION. And all the IMPROVEMENTS on a generator are added to unfoul these two things.

SELF INDUCTION

Here it is again—the voltage of self induction. This time it's upsetting ideal commutation.

Go back and look at the graph in figure 46. Notice that the current falls smoothly from 10 amperes to zero as the commutated coil passes into the neutral plane. You know what happens when a coil has a decreasing current. The flux field collapses on the coil and induces a voltage. This voltage tends to keep current flowing.

That means two voltages operating in the same coil—one induced by the field and the other induced by self induction. Consider BOTH voltages—they're both forcing current in the SAME direction. Which means that instead of the current falling quickly to zero, IT CONTINUES TO FLOW. Figure 47 shows this. The time marked with the star is the neutral plane. Follow the

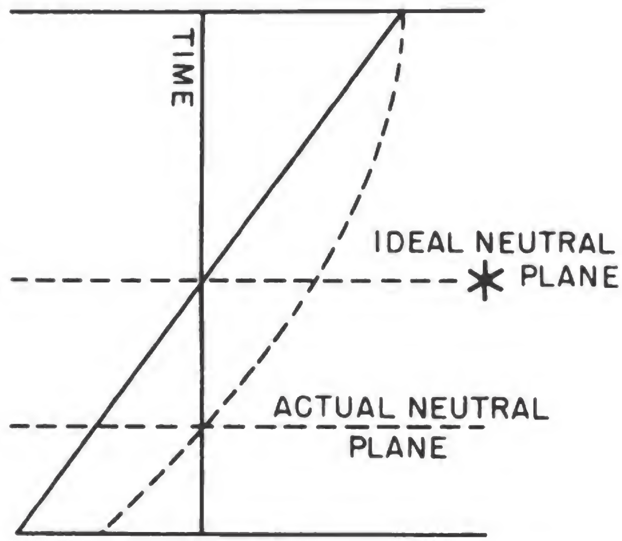


Figure 47.—Effect of self induction.

solid line. It shows you what SHOULD happen—zero current at the neutral plane. Now follow the broken line. It shows you what DOES happen—plenty of current at the neutral plane. And that means current in a short circuit.

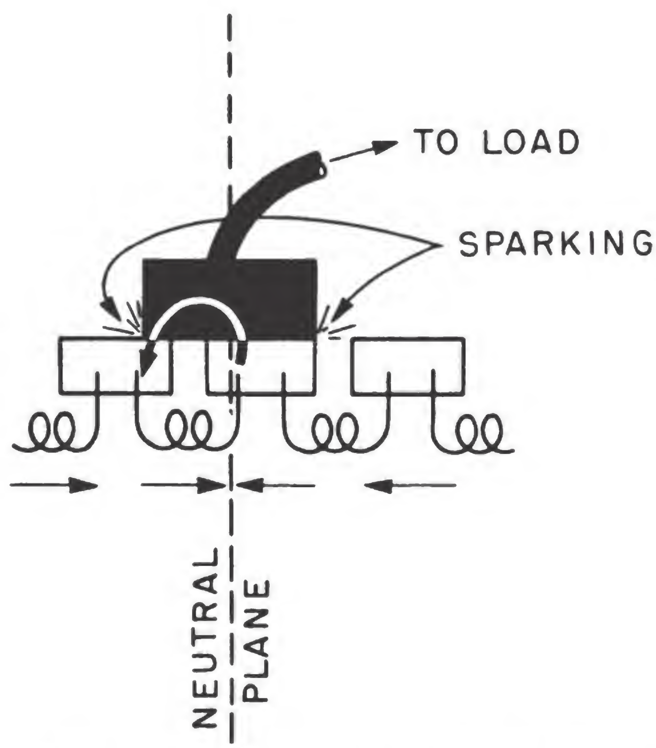


Figure 48.—Commutated coil carrying current.

Look at figure 48—it shows what the voltage of self induction does to ideal commutation. It shows what happens when

a commutated coil carries current. Even though the voltage of self induction is small, the current is high—much too high for the brush to handle. Result—current jumps from the segments to the sides of the brush. And you have arcing and a pitted commutator.

That's the first trouble maker—be sure you know how the emf of self induction fouls up ideal commutation.

ARMATURE REACTION

Every loaded generator has TWO fields present. One is the regular field produced by the field poles. And the other is the

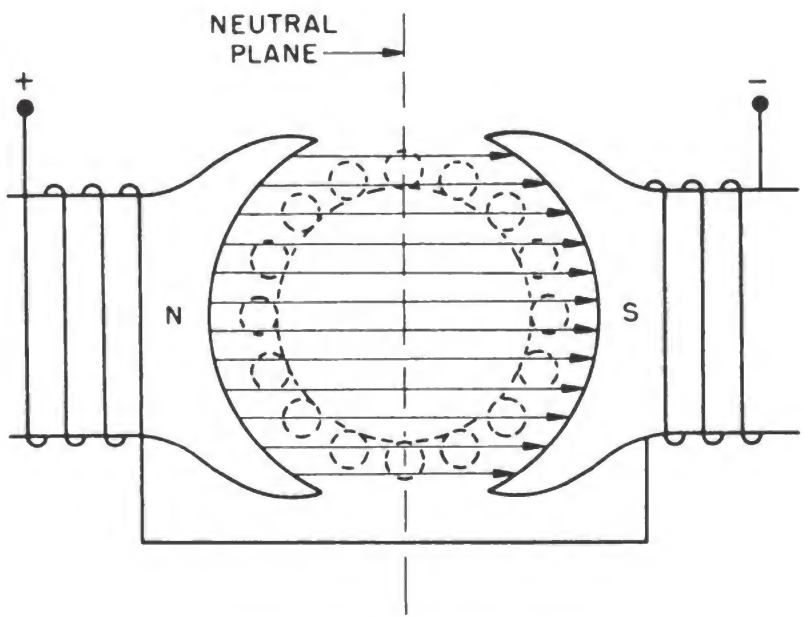


Figure 49.—Field flux alone.

field around the armature produced by the load current. These two fields work against each other causing ARMATURE REACTION. The combined field is bent and twisted out of its natural shape, resulting in FLUX DISTORTION.

First, look at the flux from the pole pieces ALONE (figure 49). It's straight across the generator. And the neutral plane is at right angles to the flux—straight up and down.

Next, look at the flux produced by the loaded armature ALONE (figure 50). Notice that this field is roughly paralleled to the neutral plane.

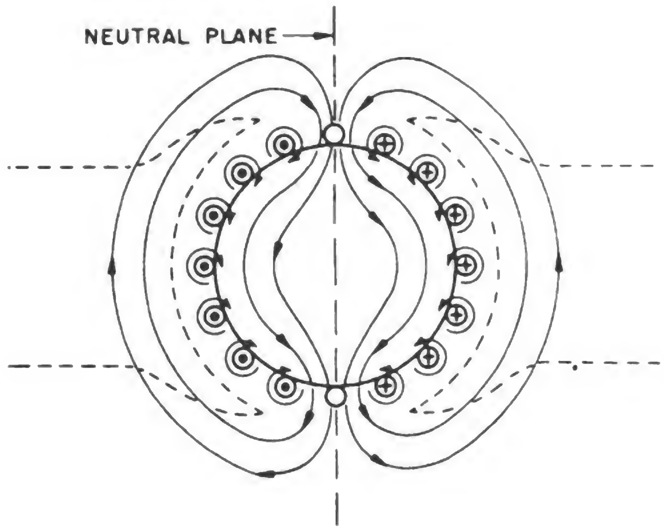


Figure 50.—Field of a loaded armature.

Now compare the two fields. One fact stands out—the two fields are at RIGHT ANGLES to each other. But you know that it is impossible for flux lines to cross at right angles. There-

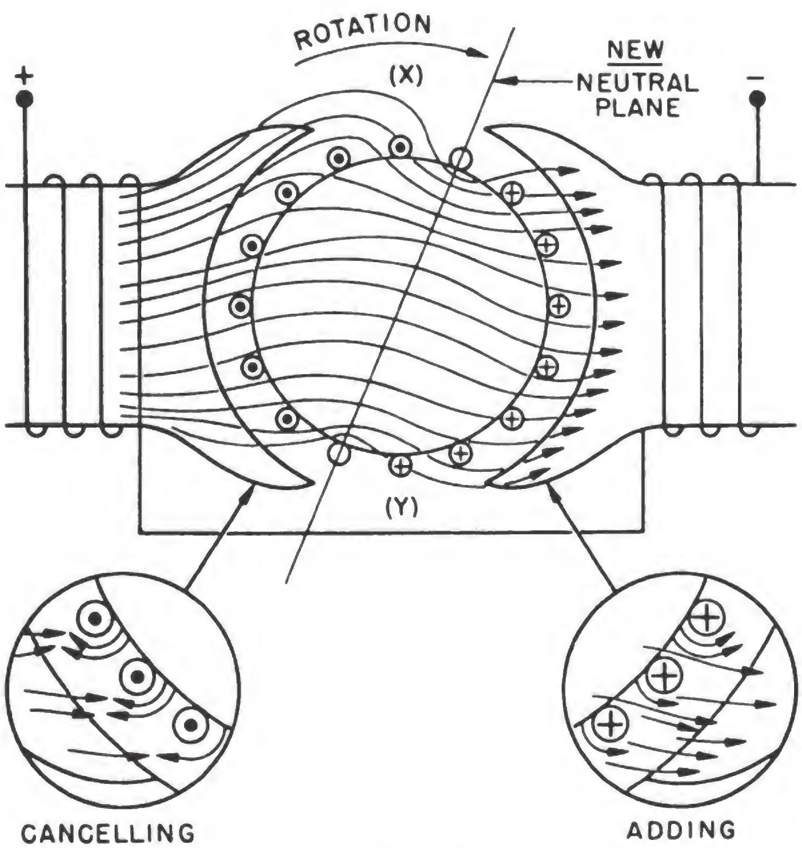


Figure 51.—Flux distortion.

fore, there must be a COMBINATION of the two fields to form a TOTAL FIELD. Combination of flux fields means either cancellation or adding. In this case, both.

Look at figure 51. It shows the TOTAL FIELD—the result of ARMATURE REACTION. Notice the twisted, distorted TOTAL field caused by the reaction of the two INDIVIDUAL fields. The normal straight field of the pole pieces has been skewed—shoved out of line by the armature field.

The exact process of distorting the field is shown in the two magnified digrams of figure 51. The two fields meet head-on in the lower left pole tip. Result—cancellation and a weak field. And the two fields meet at a small angle in the lower right tip. Result—ADDING and strengthening of the total field.

You are probably wondering why armature reaction is so important in commutation. Well, this is it—armature reaction SHIFTS the neutral plane. Notice, in figure 51, the conductors that WERE in the neutral plane are NOW cutting flux. And they're carrying current. They CANNOT BE COMMUTATED. But, if you check figure 51, you'll notice a set of coils NOT cutting flux. These coils are in a NEW neutral plane. Notice that armature reaction has shifted the neutral plane IN THE DIRECTION OF ROTATION.

Remember what the emf of self induction did? It kept current flowing in the commutated coil—even at the neutral plane. But this current must reverse. And at the instant it reverses, current stands still. It's like climbing up and down a ladder—after you reach the top you've got to reverse direction to come down again. And at the instant you reverse direction—you're stopped. Similarly, in the coil—the instant the current stops is THE INSTANT to commutate the coil. You can find that instant by looking back at figure 47. It isn't at the IDEAL NEUTRAL PLANE, BUT PAST IT—IN THE DIRECTION OF ROTATION.

PUT BOTH TOGETHER

So now you have the two "foulers" of ideal commutation. Both do the same thing—they move the plane of zero current in the direction of rotation. This new plane is called the ELECTRICAL NEUTRAL PLANE or the COMMUTATING PLANE. And that's

where the brushes go! Because that's the only place where current and voltage are zero—the only place where there will be no sparking at the brushes.

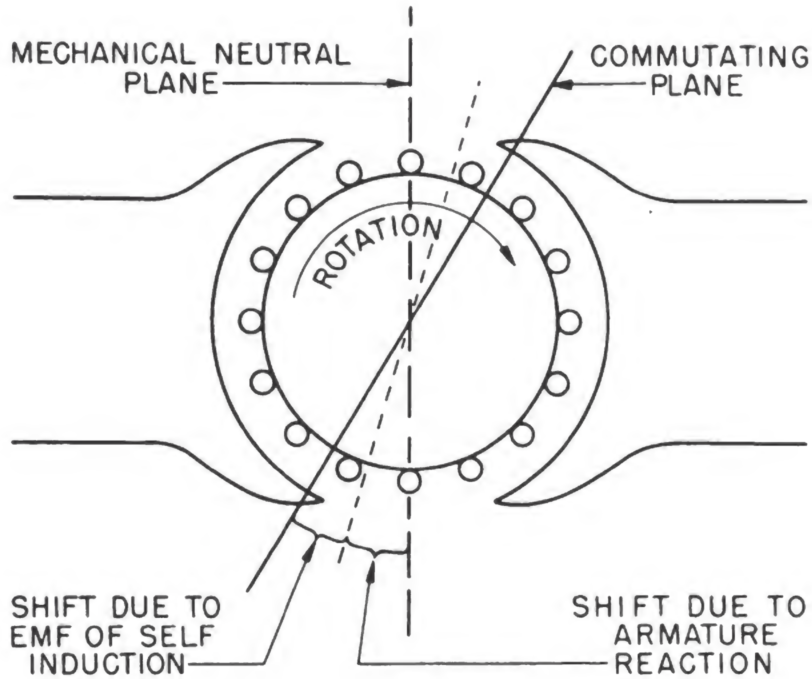


Figure 52.—The commutating plane.

Figure 52 shows both the ideal neutral (mechanical neutral) plane and the new neutral plane—the commutating plane. You can see that both the emf of self induction and the armature reaction force the commutating plane away from the mechanical neutral plane—in the direction of rotation. O.K.—that's where the commutating plane is, and that's where the brushes should go.

WHAT TO DO

It's easy enough to say "put the brushes on the commutating plane." But how can you tell where that plane is? Review the characteristics of ideal commutation—no voltage or current in the commutated coil, and no sparking. That last item, "no sparking," is your key to good commutation. When the brushes stop sparking—you've got 'em right where they belong. And that's just the way the commutating plane is located. Shift the brushes until sparking stops or is reduced to a minimum.

CHANGING LOADS

Imagine that you've got a generator all set. It's running and carrying its load with no sparking at the brushes. Suddenly the brushes start to spark. You readjust the brush position and the sparking stops.

A change in the position of the commutating plane caused the sparking. You stopped it by shifting the brushes to the position of the new commutating plane. Now the commutating plane doesn't jump around without reason. There's a mighty good reason—a change in load.

Suppose the load is increased. The current in the armature increases, because THE ARMATURE CARRIES ALL THE LOAD CURRENT. As the armature current increases, the armature field becomes stronger, the emf of self induction and the armature reaction both increase because they are both caused by the armature's field. Load changes and armature troubles go hand in hand.

Things would be simple if loads were steady. But they aren't. Every time a motor is started or stopped, and every time a light is turned on or off, the load changes. When you consider the loads on a ship's service generator, you know that most loads vary. That means a constant shifting of brushes—a new position for every change in load.

Some job—standing watch on a generator and shifting brush position every time someone turns on a light! Surprisingly enough, that's exactly what they used to do. But nowadays, it's not necessary. The troubles caused by self induction and armature reaction are taken care of inside the generator. It's almost totally automatic.

There are four ways of taking care of emf of self induction and armature reaction—SLOTTED POLE PIECES, LAMINATED POLE TIPS, INTERPOLES, and COMPENSATING WINDINGS. These are used to keep the COMMUTATING PLANE AT THE MECHANICAL NEUTRAL PLANE. In short, they cancel out the bad effects of the armature field. These are the improvements that are added to the generator to make it run BETTER and SMOOTHER.

SLOTTED POLE PIECES

You can weaken a magnetic field by putting air in the path of the flux. Now, in a generator, the question is, which field is going to get weakened?

It wouldn't be very smart to weaken the field from the poles because that would just cut down the generated voltage. So, you weaken the armature field by SLOTTING the POLE PIECES.

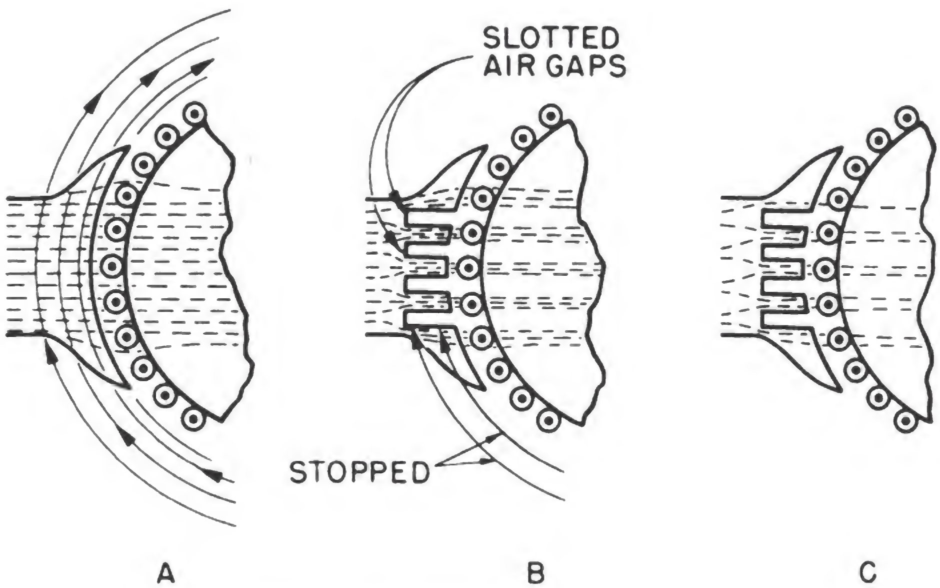


Figure 53.—Slotted pole pieces.

Look at the series of diagrams in figure 53. *A* shows an ordinary field pole with both fields present. Of course you know that two fields cannot cross like this, but the diagram shows you how the two forces approach each other. *B* shows the pole pieces SLOTTED, meaning the shoe has sections or slots cut out of its face. Air takes the place of the missing iron. Reluctance is increased—but ONLY for the armature field.

Notice how the flux from the field poles avoids the air spaces by sticking to the iron path. The MAIN FIELD IS NOT WEAKENED. Since the armature flux CANNOT AVOID the air space, the armature flux is weakened to the point where it can scarcely interfere at all with commutation.

Thus by weakening the armature flux you correct trouble makers at once, since the armature field is responsible for both emf of self induction and armature reaction.

Figure 53*C* is the diagram of the total field with slotted pole pieces. The re-alinement of the field is not PERFECT, but it's a lot BETTER than it is with solid pole pieces. The commutating plane has been moved back nearer to the mechanical neutral plane.

Slotting the pole pieces helps to improve commutation, but it doesn't do the job perfectly. The principal drawback—slotted pole pieces cannot adjust for changing loads. With a light load, only a few small slots are needed, but with a heavy load, many large slots are needed to fill the armature flux. Therefore, this method of bettering commutation is satisfactory only for fairly constant loads.

LAMINATED TIPS

LAMINATED TIPS really mean more than the name implies. In modern generators the whole pole piece, including the tips, is laminated. But when you speak of LAMINATED TIPS, you refer to a special type of lamination at the POLE TIPS only.

When a pole piece is constructed, the laminations are laid one on another to produce the proper thickness of the pole piece. When the TIPS are to be LAMINATED the same general construction is used but with a special exception.

Figure 54 shows this exception. It differs from an ordinary lamination in just one respect—ONE TIP MISSING. Now, when the laminations are LAID UP to make the pole piece, every other

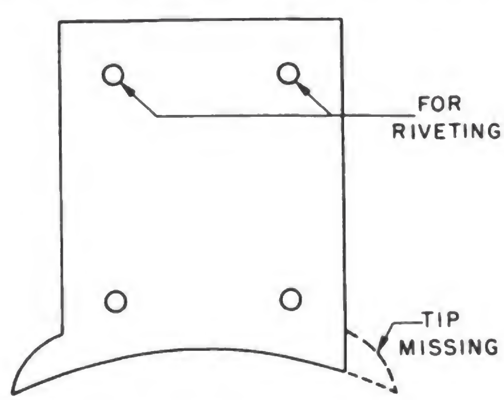


Figure 54.—One lamination.

lamination is reversed. That produces a pole piece with air gaps in each tip.

Figure 55 shows the complete pole piece. Notice that each tip has exactly ONE-HALF THE IRON of a normal pole piece. One-half the iron accommodates just one-half the flux, thus weakening the field around the pole tips. Now go back to figure

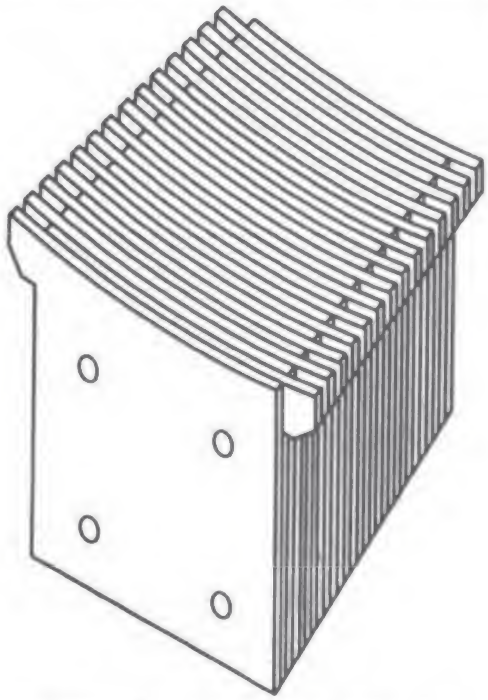


Figure 55.—Laminated pole tip.

51. Notice how the DISTORTED FIELD concentrates in UPPER LEFT and LOWER RIGHT solid pole tips. With laminated tips, this concentration is impossible because there isn't enough iron to carry that much flux.

The total effect of laminated tips is to prevent the concentration of flux at the pole tips. If the flux cannot concentrate at the tips, much of the distortion is removed.

Laminated pole tips do just about the same kind of a job done by slotted pole pieces. Both remove the commutating plane closer to the mechanical neutral plane. The correction isn't perfect, but it helps. The main drawback is, again—no adjustment to changing loads.

INTERPOLES

Look at figure 56. You can see what's wrong, there's no correction for armature reaction.

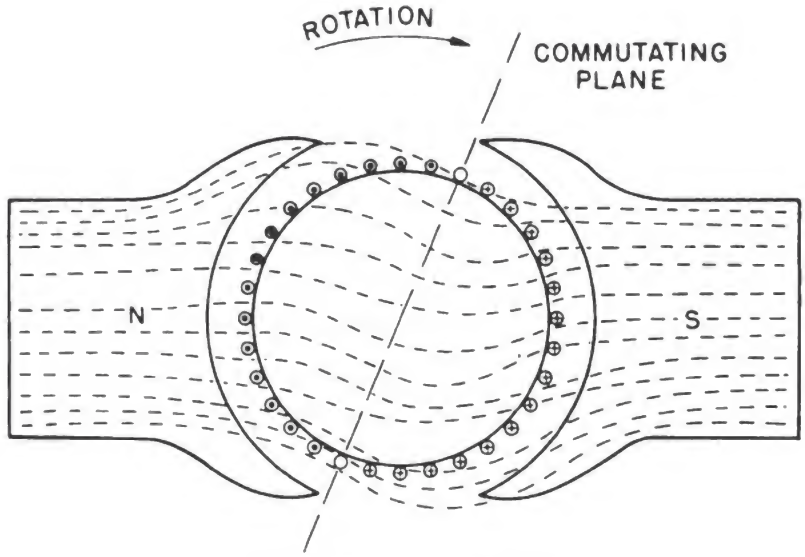


Figure 56.—No interpoles.

Now look at figure 57. Two INTERPOLES, commutating poles, are added AT THE NEUTRAL PLANE. Notice the action of these interpoles on the total generator flux. It looks almost as though the interpoles actually made the flux distortion worse. But they haven't. The interpoles do TWO things at once.

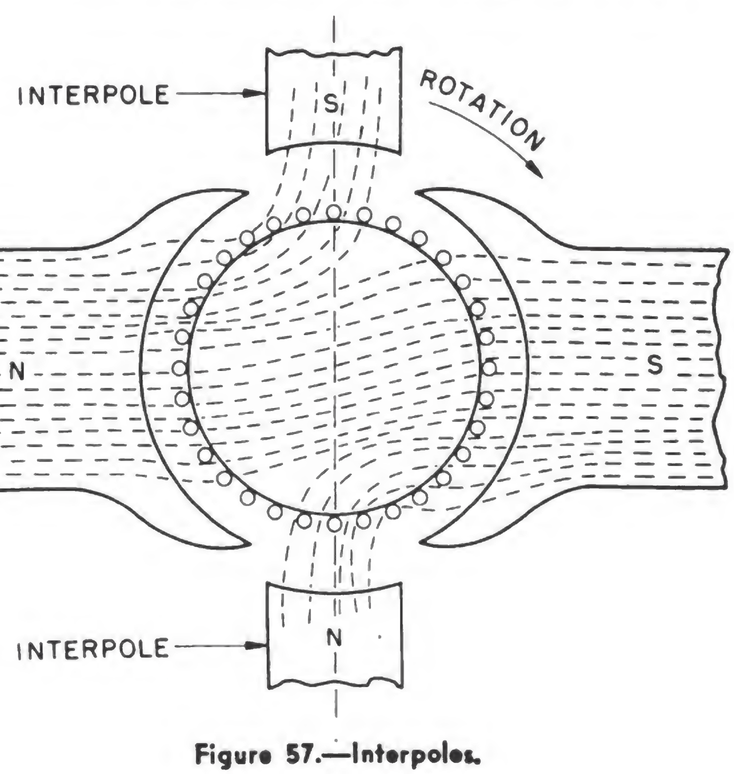


Figure 57.—Interpoles.

First, interpoles offset the emf of self induction. Figure 57 shows how this is done. The coil of the interpole in the mechanical neutral plane is carrying current caused by the emf of self induction. To get rid of that self induction, you need a flux field that will induce an OPPOSITE emf. The interpole furnishes that field. Prove it by the generator hand rule. In figure 58, the three armature conductors in or near the neutral

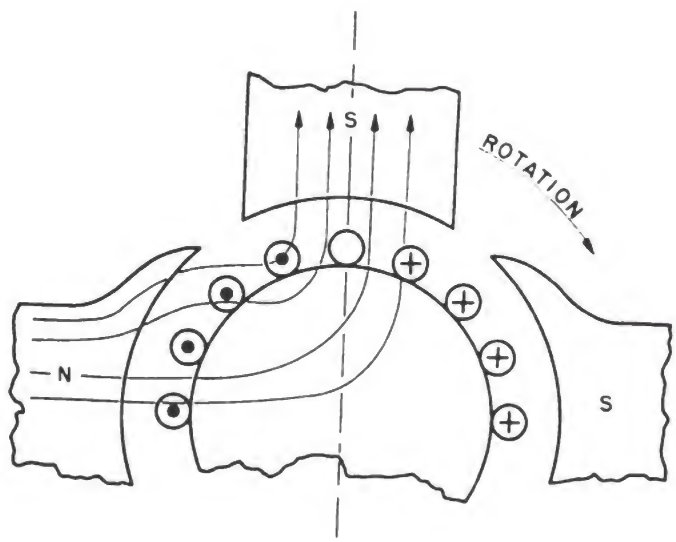


Figure 58.—Interpoles and self induction.

plane are all cutting INTERPOLE FLUX. The rest is easy—the interpole flux is made just strong enough to balance exactly the flux that produces the emf of self induction.

That sounds like a rosy picture. You get rid of the emf of self induction, and your commutating plane shifts right back to the mechanical neutral plane. That means no brush shifting to get good commutation. Instead the brushes ride right on the mechanical neutral plane, because the mechanical neutral and the commutating planes are the same.

Now for the other function of interpoles—to correct partly for armature reaction. Figure 59 shows this action. To begin with, this diagram is not the whole story. Only the armature field and the interpole field are shown. The field from the main poles is missing but if the main field were included in the diagram, it would be too messy for you to see the action clearly.

The most important thing for you to see is the CANCELLING ACTION of the interpole. Notice how the armature flux is forming a north pole at the bottom. Also observe how the north pole flux of the armature meets the north pole flux from the interpole head on. That can mean just one thing—CANCELLATION. You get rid of armature flux and armature reaction.

There are the two actions of the interpoles—to offset the emf of self induction and partly correct the armature reaction. Notice the word "partly" applied to armature reaction correction. Here's the reason for it. Armature reaction goes on ALL

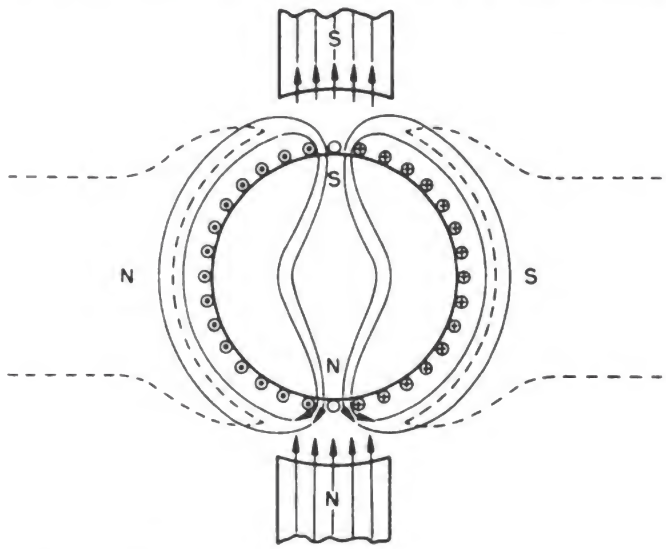


Figure 59.—Interpoles and armature reaction.

AROUND the armature. But the interpoles act only in the SMALL AREAS near the neutral plane. In short, the interpoles are too small to correct all of the armature reaction. Their main function is to kill off the emf of self induction. And they do a good job of that. Interpoles do a better job of making commutation "right" than either slotted pole pieces or laminated tips.

Neither the slotted pole pieces nor the laminated tips have any adjustment for changing loads, but interpoles have. And it's the simplest kind of adjustment. Interpole windings are connected in series with the armature. That makes adjustment automatic. The interpoles' field strength changes automatically with every change in load.

Every ampere of load current causes commutation troubles. At the same time, every ampere of load current goes through

the interpole winding. Thus the current that CAUSES commutation troubles CORRECTS those same troubles when it gets in the interpole winding.

Nice system. But it won't work unless you've got two things right. First, the interpole must be connected in SERIES with the armature. Figure 60 shows you the correct connection—both schematic and wiring diagrams. Second, the interpole must have the correct POLARITY. An easy rule for interpole polarity

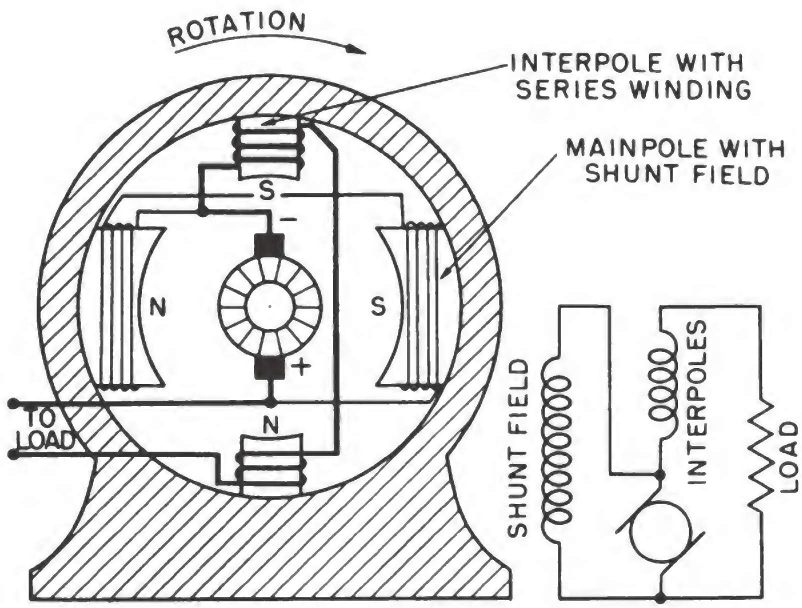


Figure 60.—Interpole connections.

is based on the interpole action. Remember that action must offset the emf of self induction. Therefore, interpole flux must be the same as the flux of the next main pole. In fact, the interpole acts like an extension of the next main pole. So here's the rule—in generators, THE INTERPOLE POLARITY IS ALWAYS THE SAME AS THE NEXT MAIN POLE IN THE DIRECTION OF ROTATION.

COMPENSATING WINDINGS

Interpoles do an excellent job of correcting for the emf of self induction. But they aren't so good on the job of knocking off the armature reaction. Since interpoles occupy such a small percentage of the total space in the field, they can eliminate

the armature flux in only that small space. If you could plant interpoles all around the armature, their flux would be effective over the whole surface of the armature. Something like that is done in COMPENSATING WINDINGS.

The compensating windings are set in slots in the main pole shoes. The current direction in these windings is always OPPOSITE to the CURRENT DIRECTION of the ARMATURE WINDINGS. Compare the currents of the armature and compensating windings in figure 61. You'll notice that they're opposite.

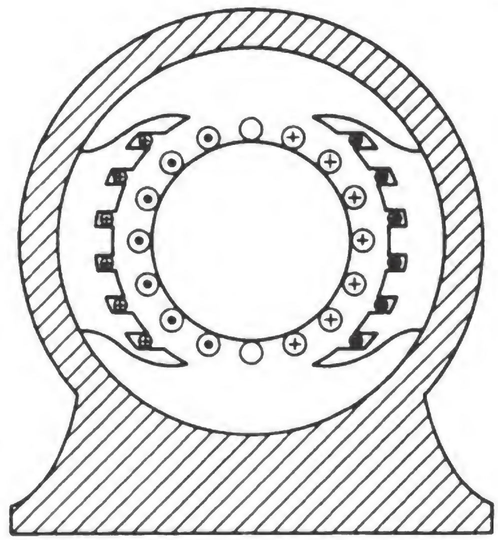


Figure 61.—Compensating windings.

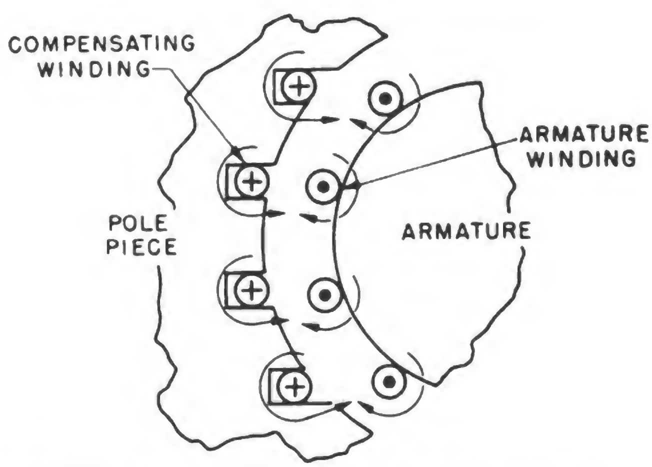


Figure 62.—Compensating winding action.

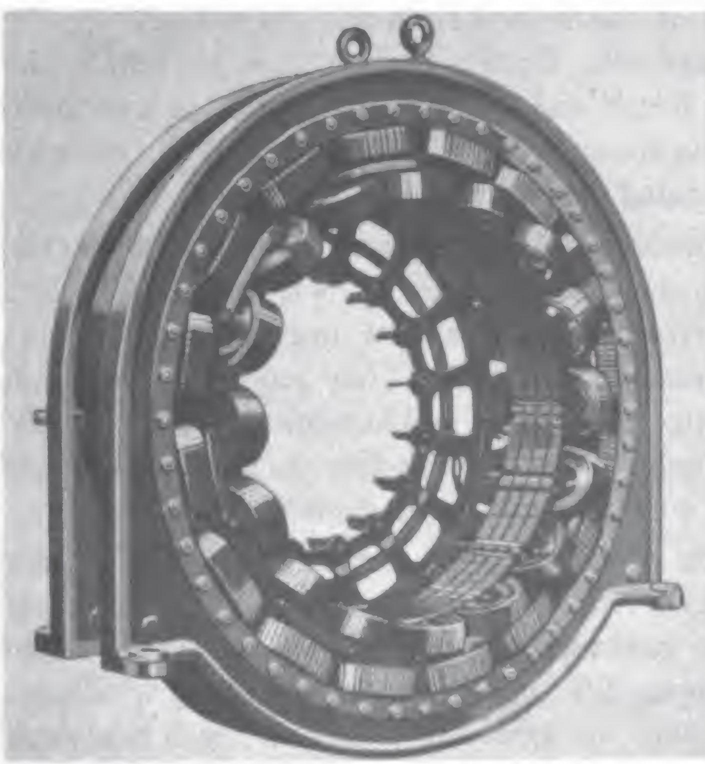
The enlarged sectional diagram of figure 62 shows you the action of compensating windings. Notice how the COMPENSATING FLUX is OPPOSITE to the ARMATURE FLUX. That means cancellation. And if you get rid of armature flux, you get rid

of armature reaction. Also, if you get rid of armature flux, you eliminate the emf of self induction—at least partly. And right there is the main drawback of compensating windings. They don't do a very good job on emf of self induction. That's because compensating windings are not concentrated at the neutral plane—the one spot they would have to be to eliminate emf of self induction.

Are compensating windings automatic in adjusting for changes in load?

Absolutely—they're in series with the armature, just like interpoles. It's the same set-up. More load current means more ARMATURE flux. And more load current means more COMPENSATING WINDING flux. The two fluxes depend on the same current so they are always about the same strength. The same strength and opposite in direction—just about complete cancellation.

Another nice system for getting the commutating plane back to the mechanical neutral plane for all loads. That's compensating windings! But they won't work unless two things are right. First, the windings must be in SERIES with the armature. Second, they must carry current OPPOSITE to the armature



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current. The schematic of figure 60 gives you the connection—just put compensating windings in place of the interpoles.

You're probably wondering just how the compensating windings are put on the field poles. Figure 63 shows you. This is a multi-polar generator without interpoles, just compensating windings. Notice that the compensating windings are in the form of coils, that they overlap two main poles, and that they're heavy enough to carry the full armature current.

SUMMING IT UP

THE PROCESS—COMMUTATION is the process of taking current off a rotating armature and delivering it to a stationary load circuit. The whole process is bound up in the contact between the commutator and the brushes. Under IDEAL conditions, the process is a pipe. By commutating the coil while it is in the neutral plane, you get NO VOLTAGE and NO CURRENT in the commutated coil. Result—NO SPARKING, and the generator delivers rated current and rated voltage.

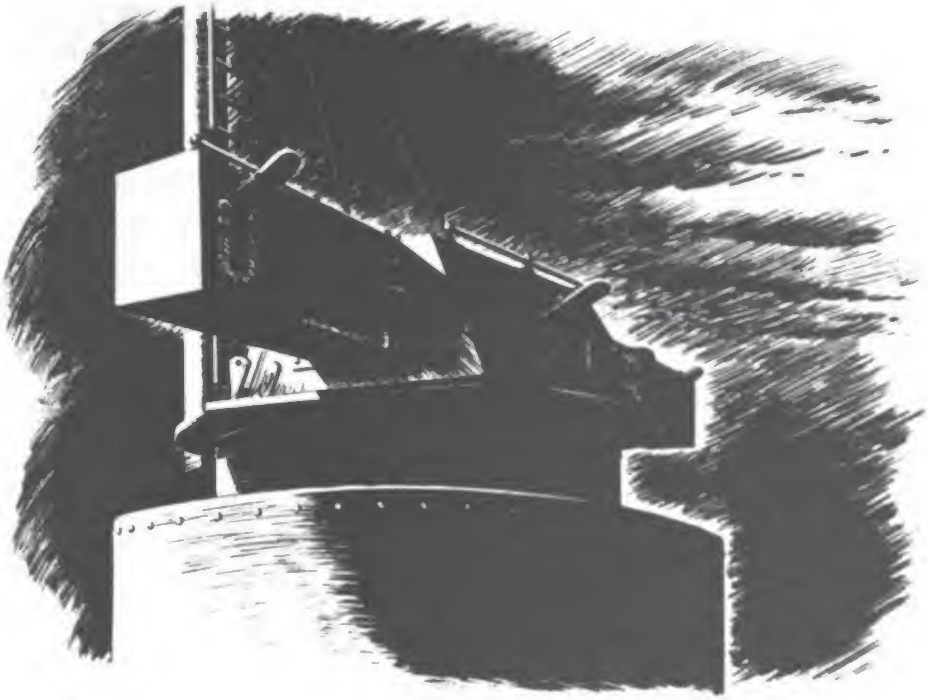
THE TROUBLES—ARMATURE REACTION AND EMF OF SELF INDUCTION. Both result from the flux field of the armature, and both foul up the NO VOLTAGE and NO CURRENT condition of the commutated coil. Both act to maintain current in the coil. Result—the brush and commutator system is overloaded. Arcing occurs, the commutator is damaged, and the generator delivers less than rated current and voltage.

THE REMEDIES—SLOTTED POLE PIECES, LAMINATED TIPS, INTERPOLES, and COMPENSATING WINDINGS. The first two reduce the effect of the armature flux by increasing the reluctance of the armature flux path. They put air into the magnetic circuit. Slotted pole pieces and laminated tips are purely MECHANICAL features. They cannot adjust to load changes and generally are used only on constant load machines.

The last two, interpoles and compensating windings, reduce the effect of armature flux by setting up an opposing flux field. They are ELECTRICAL features, which adjust automatically to load changes. Interpoles and compensating windings are always in series with the armature—their strength is always controlled by armature current.

DETAILS OF DESIGN

You'll never have to design a generator. But it won't hurt you any to know what to expect when you pull off an end bell. Generally, you'll find laminated tips and slotted pole pieces on constant load jobs. And usually you'll find interpoles or compensating windings on variable load jobs. But, there is no set and fast rule—in fact, you may find all four features in the same machine. The use of interpoles AND compensating windings is especially common in big jobs.



CHAPTER 6

D.C. GENERATORS—VOLTAGE REGULATION AND CONTROL

VOLTAGE—UP AND DOWN

All of you have had the unpleasant experience of having the voltage rise and fall as the load on the generator is changed. It caused the motors to gain or lose speed, lights to brighten or dim, depending on whether the voltage went up or down.

Many times an abrupt drop in voltage is more serious than an inconvenience. It could hamper the operation of pumps, deck machinery, and electric lifts to the extent that it is dangerous for the operators.

Some generators have a natural tendency to allow the voltage to drop. Others are capable of maintaining a more nearly constant voltage regardless of the load. This chapter is a discussion of these generator characteristics and of the systems used to control the voltage.

The term VOLTAGE REGULATION refers to any change in the generator terminal voltage that is caused by a change in LOAD CURRENT. Sometimes this change in voltage is known as the EXTERNAL CHARACTERISTIC of the generator.

The degree of VOLTAGE REGULATION is a mathematical comparison of the terminal voltage at NO load with the terminal voltage at FULL load when the generator is being driven at a CONSTANT SPEED. It is expressed as a percentage of the full-load voltage.

For example, if the no-load voltage of a generator is 120 and its full-load voltage is 110, the percent of regulation is—

$$100 \times \left(\frac{120 - 110}{110}\right) = 9.09\%$$

Voltage regulation of a generator is determined by its design. VOLTAGE CONTROL is any change in the output produced by an ADJUSTMENT, either manual or automatic, to the generator.

VOLTAGE DROPS IN A SEPARATELY-EXCITED GENERATOR

The generator pictured in figure 64 is separately-excited and driven at a constant speed.

In figure 64*A*, an emf of 125 volts is indicated by the voltmeter. Since the voltmeter is connected across the brush terminals, 125 volts is the GENERATED VOLTAGE E_g and also the TERMINAL VOLTAGE E_a.

In figure 64*B*, the same generator, running at exactly the SAME SPEED and cutting the SAME FLUX field, shows a potential of only 110 volts between the brush terminals.

Here's the difference. In figure 64*A*, the generator is running without load. That means no current is flowing except the small current through the voltmeter. But in figure 64*B*, the generator is supplying 50 amperes to a load.

From your knowledge of armatures, you know the current that flows through the load also flows through the armature. Since all armatures have some resistance, you will have an IR drop across the armature.

The generator in figure 64 has an armature current I_A of 50 amperes, and the resistance R_A of the armature circuit is 0.2 ohms. Therefore, the IR drop across the armature is—

$$E = IR = 50 \times 0.2 = 10 \text{ volts.}$$

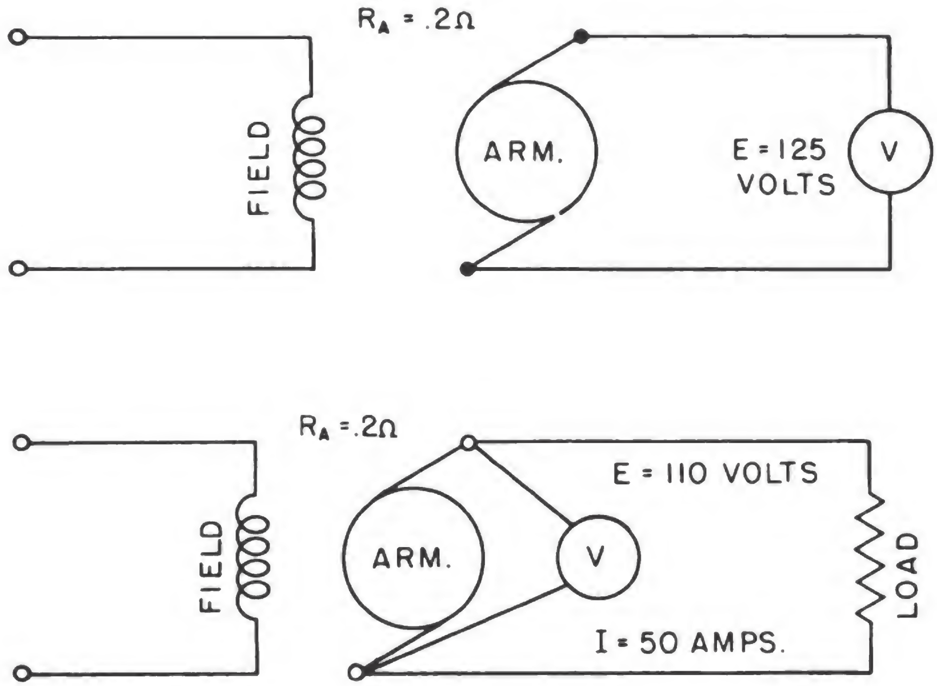


Figure 64.—IR and AR drop in a separately excited generator.

These 10 volts are "used up" before they reach the generator terminals. Therefore, output voltage is 10 volts less than the voltage generated—125 — 10 = 115 volts.

But the voltmeter indicates only 110 volts. What happened to the other five volts?

Remember how ARMATURE REACTION affected the flux field? Armature reaction WEAKENS the MAIN FLUX FIELD. As the load goes up, armature reaction goes up, field flux is weakened, and the output voltage goes down. In short, BECAUSE OF ARMATURE REACTION, ANY INCREASE IN LOAD WILL CAUSE A DECREASE IN OUTPUT VOLTAGE. This is called the *AR* DROP. In the generator of figure 64*B*, the AR DROP accounts for five volts.

Thus the full-load terminal voltage for this separately-excited generator is—

$$E_t = E_g - I_A R_A - \text{AR} = 125 - 10 - 5 = 110 \text{ volts.}$$

Remember—any increase in load on a separately-excited generator causes a decrease in terminal voltage. Two drops cause this decrease—IR drop and AR drop.

HOW TO CALCULATE PERCENT OF REGULATION

Suppose 50 amperes is rated full-load current for the generator in figure 64*B*. Find the voltage regulation for the generator.

$$\text{Regulation} = \left(\frac{\text{No-load Voltage} - \text{Full-load Voltage}}{\text{Full-load voltage}} \right) \times 100$$

For this generator—

$$\text{Regulation} = \left(\frac{125 - 110}{110} \right) \times 100 = 13.64\%$$

VOLTAGE DROPS IN A SHUNT WOUND GENERATOR

Figure 65 is a schematic diagram of a shunt generator. The shunt-field leads are connected to the brush terminals. You know the field excitation depends upon the terminal voltage of the generator. In other words, if the terminal voltage goes down, the field flux is cut down. Any decrease in field flux causes a decrease in generated voltage. Any decrease in generated voltage causes a corresponding decrease in terminal voltage.

IR and *AR* drops affect the terminal voltage of a shunt generator just the same as they affect the terminal voltage of a

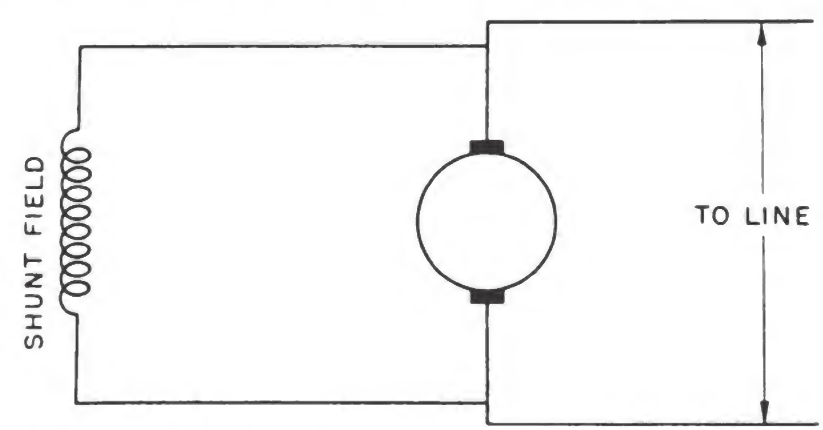


Figure 65.—Schematic diagram of a shunt generator.

separately-excited generator. In a shunt generator, the decrease in terminal voltage caused by *IR* and *AR* drops weaken the

field of the generator. The weakened field causes a further reduction in the terminal voltage.

Thus, the terminal voltage of a shunt generator running at a constant speed is influenced by three factors each time the load increases—

IR drop in armature circuit.

AR drop caused by increased armature reaction.

Decreased field excitation.

Therefore, when a shunt generator is heavily overloaded the output voltage will drop to almost zero, because voltage is

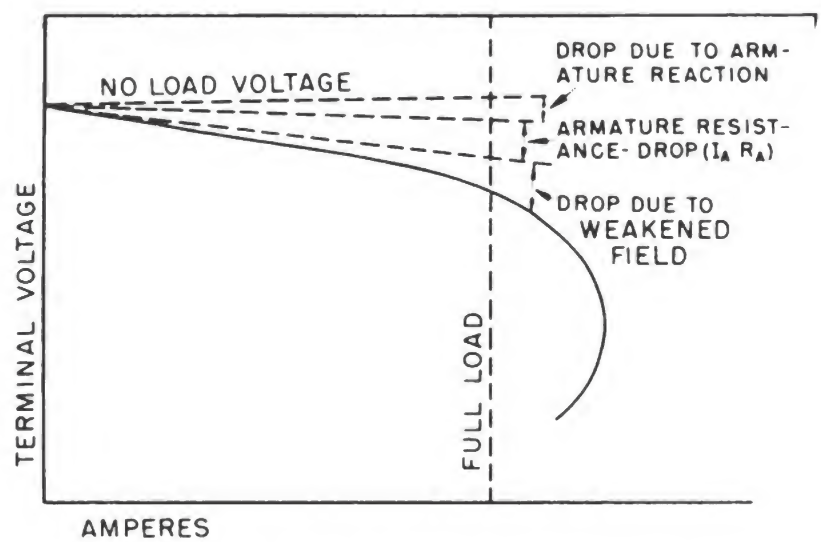


Figure 66.—Voltage output of a shunt wound generator.

generated from only the residual magnetism of the field. This self-regulation feature protects the shunt generator against damage from short circuits. If you short the armature terminals of a shunt generator, the voltage falls to almost zero.

Figure 66 is a graph of voltage regulation of a shunt generator. Notice that the voltage drop from no-load to full-load does not make a straight line. The rate of drop increases as the load approaches the full-load value. When the rated full-load value is exceeded, small increases in load cause the voltage to drop still faster.

The characteristic of the shunt generator shown by the graph in figure 66 is sometimes called a DROOPING POWER CHARACTERISTIC

WHAT TO DO ABOUT VOLTAGE REGULATION

You can't get rid of the *IR* drop in the armature circuit, but you can keep it down by making the armature resistance as low as possible. That means—no loose leads, no loose connections, clean commutator, and the correct brushes seated properly on the commutator.

You can reduce the *AR* drop by reducing armature reaction. You learned how to do that in Chapter 5.

Since you can't eliminate completely either the *IR* or *AR* drop, in a shunt generator you will still have some voltage drop due to a weakened field. But you can offset the weakened field by putting a RHEOSTAT in series with the shunt field. This rheostat varies the resistance of the field circuit. Consequently, by adjusting the resistance of the rheostat, you can hold the generated voltage fairly constant IF the load isn't changing too much or too rapidly.

The large VOLTAGE REGULATION of shunt generators makes them inefficient when widely varying or frequently changing loads are present.

COMPOUND GENERATORS

Most electrical circuits require a nearly constant voltage. If shunt generators are used to supply these circuits, variations of load will produce undesirable voltage variations—unless you adjust the field rheostat each time the load changes.

Voltage variations caused by load fluctuations can be remedied by the use of a COMPOUND GENERATOR, one which has a SERIES FIELD as well as a shunt field. The SERIES FIELD CARRIES THE LOAD CURRENT, and the series field strength varies as the load varies. If the load goes up, the series field flux increases; and if the load goes down, the series field flux decreases.

Here's how the series field helps to overcome voltage variations. The series field winding is so connected that it AIDS the shunt field. This connection gives you a CUMULATIVE COMPOUND GENERATOR, meaning that any change in load current causes a corresponding change in field strength without adjusting the field rheostat. As the load increases the field, both strength and voltage increase.

The AMOUNT of increase in field flux and voltage depends upon the NUMBER OF AMPERE TURNS in the series field. If the series field has just enough ampere-turns to compensate for the *IR* and *AR* drops, the generator is FLAT COMPOUNDED, and has the SAME VOLTAGE at no-load and full-load when the series field has fewer than just enough turns to produce a flat-compounded generator, the *IR* and *AR* drops are not offset. The voltage will vary somewhat with load, but not as much as a shunt generator. This type generator is said to be UNDER-COMPOUNDED.

When the series field has more than enough ampere-turns to offset *IR* and *AR* drops, the generator is OVER-COMPOUNDED, and the voltage rises as the load goes up.

The curves in figure 67 show some of the external characteristics that can be obtained by varying the ampere-turns of the series field. The voltage curve *B* for the FLAT-COMPOUNDED generator shows that the THREE CAUSES of VOLTAGE DROP in a shunt generator can be completely overcome. The voltage curve *A* for the OVER-COMPOUNDED generator shows that the voltage can actually be made to INCREASE from no-load to full-load conditions.

You can see from the curve for the flat-compounded generator that the voltage isn't exactly constant. That is practically impossible. But the series field is adjusted so that the terminal voltage will rise only slightly and will then drop back again, eventually reaching the same value at full-load as at no-load. This small rise is generally about 5 percent, and almost any load can stand that much variation.

Also notice that with all three curves—*A*, *B*, and *C*—once the rated full-load current is exceeded, the voltage drops very rapidly, just as does the voltage of the shunt generator.

SERIES FIELD REVERSED

A differentially compounded generator is one where the series field is connected in opposition to the shunt field. As the load increases, the series field strength increases. Since the series field opposes the shunt field, the whole field will be WEAKENED and the voltage will go down much faster than if the generator didn't have a series field at all.

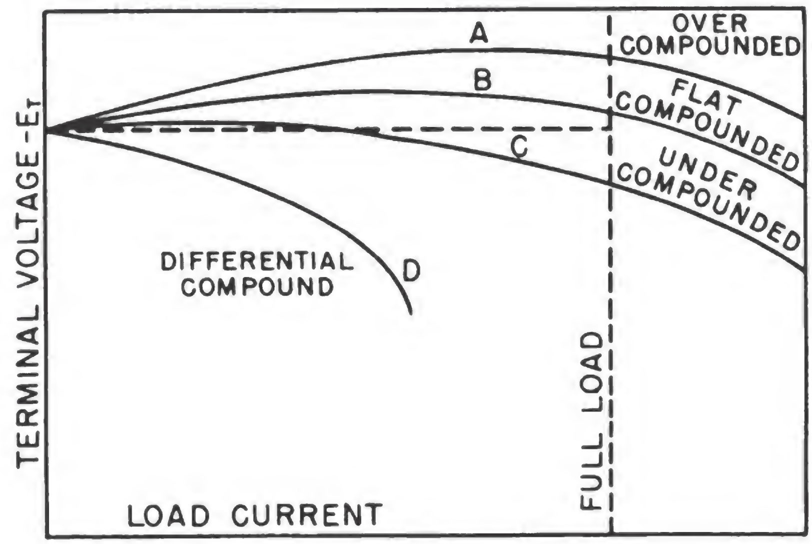


Figure 67.—Voltage characteristics of compounded generators.

The characteristics of the four compound generators are given in figure 67.

VOLTAGE CONTROL

COMPOUND-WOUND generators can provide a constant voltage under wide conditions of loading. For this reason, they were originally used to generate direct-current for the ship's electric system. However, SHUNT-WOUND generators have certain design advantages—principally their greater SIMPLICITY in design and RELIABILITY when connected in parallel with other generators. For this reason, STABILIZED SHUNT WOUND generators with a voltage regulation of about 12 percent are now used in most d.c. ship systems.

A stabilized shunt generator is simply a shunt generator with an EXTREMELY LIGHT SERIES WINDING. It has just enough series field to keep the regulations at about 12 percent. Thus, the d.c. generators installed on shipboard today have a DROOPING-POWER characteristic. Voltage control is obtained by manual or automatic adjustment of the field rheostat.

Where the load is fairly constant, as on the auxiliary d.c. generator aboard most ships, the voltage is adjusted by a hand-operated rheostat.

However, not all d.c. generators on shipboard carry constant load. In fact, the load changes are often large and frequent.

Under these conditions, voltage control by manually-operated rheostat becomes unsatisfactory and some type of automatic voltage control is necessary.

VOLTAGE REGULATOR

VOLTAGE REGULATORS are used on the Navy's d.c. generators only when unusually close voltage regulation is needed. The voltage regulations used vary widely in type and design. No attempt will be made here to describe the construction and operation of each type. Manufacturer's instruction books will give you detailed information on the construction and operation of any type voltage regulator on your ship. But to give you a general idea of their operation, look at figure 68.

This regulator operates by rapidly opening and closing a shunt circuit across the field rheostat, once the field rheostat has been manually set for the desired voltage.

HERE IS HOW IT WORKS

The RELAY MAGNET *C* has a U-shaped iron core with two solenoids, wound in opposition to each other. When both solenoids are energized, the pull of the relay magnet is weak-

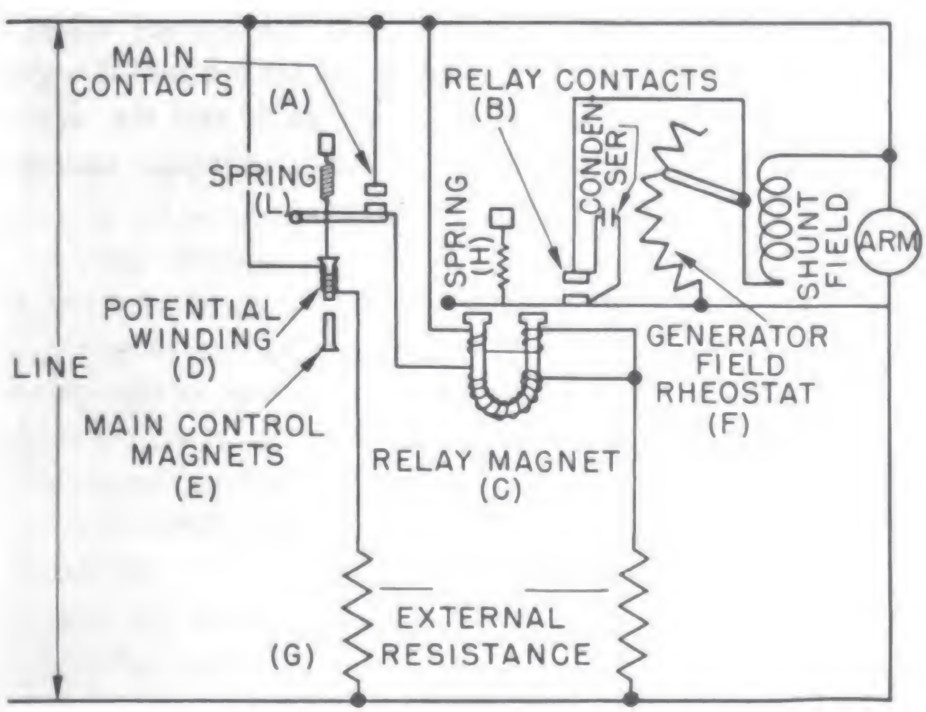


Figure 68.—Circuit for an automatic voltage regulator on a d.c. generator.

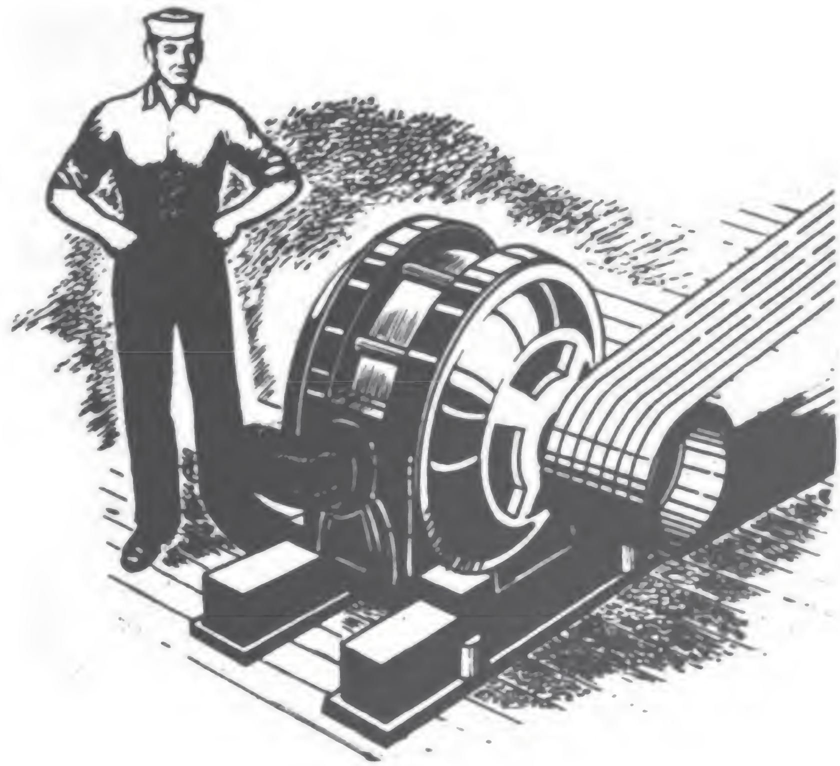
ened, and the spring *H* closes relay contacts *B*. When the relay contacts are closed, the rheostat is shorted out and the field current increases, causing the voltage rise.

A slight INCREASE in voltage causes the main control magnet *D* to open the main contacts *A*, thereby opening the circuit through one of the solenoids on the relay magnet. This solenoid is de-energized and no longer opposes the other solenoid. The pull of the relay magnet *C* is now strong enough to overcome the tension of the spring *H* and open contact *B*. The rheostat is no longer shorted out, the field current is REDUCED, and down goes the voltage. Actually both relays are VIBRATING CONSTANTLY so that the voltage changes of the generator are very small. The frequency of the vibrations determines the amount of voltage regulation.

Another type of voltage regulator consists of a SOLENOID and a number of RESISTANCE PLATES stacked one over the other. The resistance plates are connected in series with the field, and their TOTAL RESISTANCE is varied by TILTING the plates.

If the generator voltage rises above the selected value, the pull of the solenoid TILTS the plates apart and the resistance of the field circuit is INCREASED. This DECREASES the field excitation, and the generated voltage goes down.

If the generated voltage goes below the correct value, the pull of the solenoid is reduced and the plates are pulled together by a spring. This DECREASES the resistance, and the field excitation INCREASES. The increase in field excitation causes the generated voltage to go up.



CHAPTER 7

D.C. MOTORS

MOTOR CLASSIFICATION

If you were asked to choose a motor to do a certain job, there are a few things you would need to know about the job before you selected the motor. For instance, you would like to know how large a load the motor would have to pull, whether it is going to be operated in a place where gases could be ignited by sparks, or whether the air is full of abrasive materials. The possibility of a motor being subjected to dripping water or oil, or even operated under water must be considered. And you would need to know whether the voltage is to be constant or changing.

To aid you in selecting the right motor for the job, motors are classified according to the following types—

Degree of enclosure.

Method of cooling.

Speed.
Duty.
Type of field winding.
Voltage.

DEGREE OF ENCLOSURE

With reference to their degree of enclosure the following types of motors are found on board ship—

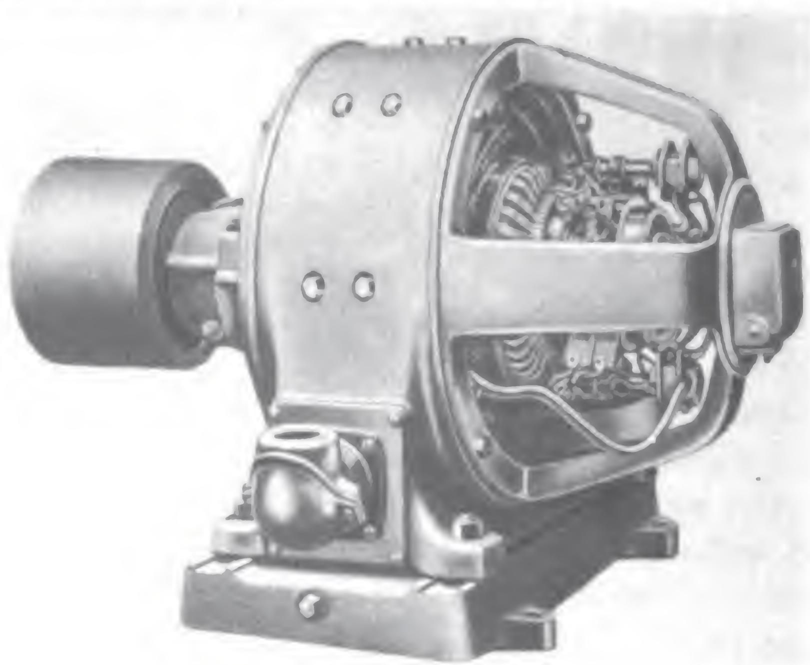


Figure 69.—Open type motor.

OPEN TYPE—The motor in figure 69 has END BELLS which offer little or no restriction to ventilation.

DRIP PROOF MOTOR—A drip proof motor, figure 70, is protected against falling moisture or dirt from any direction up to 45° from the vertical.

SEMI-ENCLOSED—A motor of this type has all ventilation openings protected with wire screens or perforated covers, as shown in figure 70. The openings do not exceed an area of one-half square inch.

ENCLOSED—An enclosed motor like the one in figure 71 is totally enclosed, except for openings provided for the admission and discharge of air. These openings often are connected to inlet and outlet ducts or pipes.

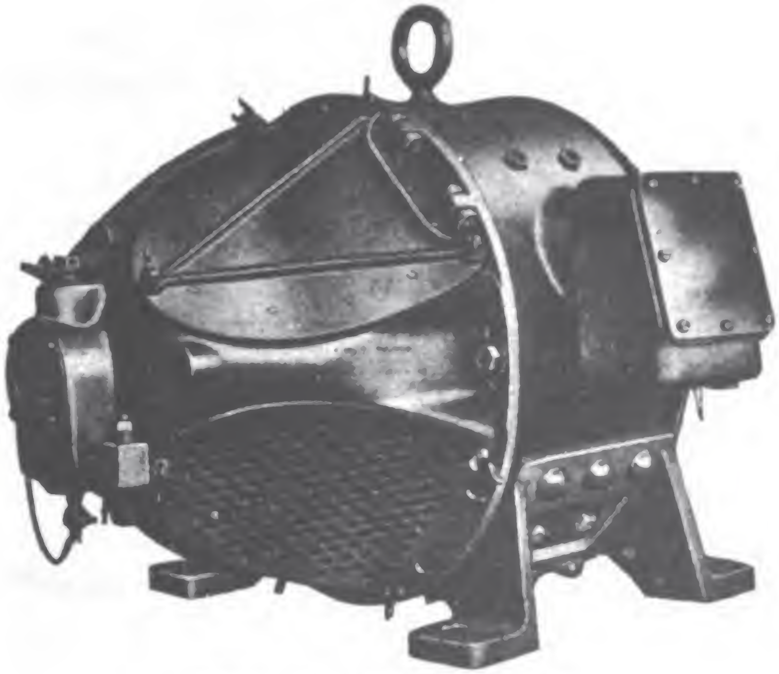


Figure 70.—Drip proof motor.

WATERPROOF—A waterproof, gastight, or dustproof motor is so constructed that a stream of water from a hose may be played upon it from any direction without leakage into the motor.

SUBMERSIBLE—A submersible motor is one that will operate under water.

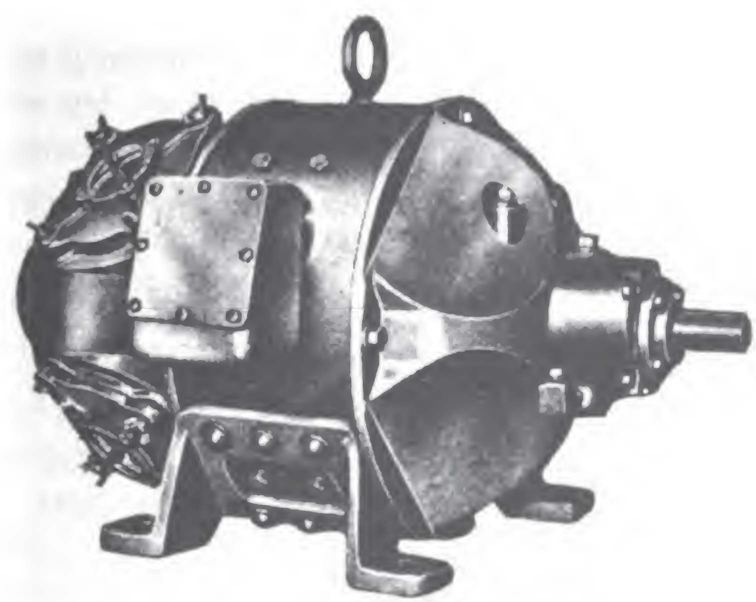


Figure 71.—An enclosed type motor.

METHOD OF COOLING

With reference to cooling the following types of motors are found aboard ship—

Natural ventilated—The natural ventilated type motor is cooled by the natural circulation of air caused by the motor's own rotation.

Self ventilated—This type motor is cooled by a fan attached to the armature of the motor.

Separately ventilated—The separately ventilated motor is cooled by an independent fan or blower apart from the motor.

MOTOR CLASSIFICATION ACCORDING TO SPEED

According to their load-speed characteristics, motors are classified as follows—

Constant speed—A motor whose speed varies only slightly between no-load and full-load. The shunt motor is a good example of this type.

Multispeed—A multispeed motor is one which can be operated at any one of several definite speeds, each speed being practically constant. These motors CANNOT BE OPERATED AT INTERMEDIATE SPEEDS. A motor with two windings on the armature is an example of a multispeed motor.

Adjustable speed—An adjustable speed motor is one whose speed can be varied gradually over a wide range, but when once adjusted remains practically unaffected by load changes.

Varying speed—In this motor the speeds varies with the load. Ordinarily the speed decreases as the load increases.

Adjustable varying speed—In this type of motor the speed may be adjusted over a wide range for any given load, but when the speed is adjusted at a given load, it will vary with any change in load.

DUTY

All motors on board Naval vessels are classified according to the duty they are to perform.

A CONTINUOUS DUTY motor is a motor capable of being operated continuously at its rated output without exceeding specified temperature limits.

An INTERMITTENT DUTY motor is capable of being operated at its rated output for a LIMITED PERIOD without exceeding its specified temperature limit.

TYPE OF WINDINGS

Motors on Naval vessels are also classified according to the field windings.

In a SHUNT MOTOR the main field winding is connected in parallel with the armature.

The SERIES MOTOR has its field winding connected in series with the armature.

The STABILIZED SHUNT motor has a LIGHT series winding in addition to the parallel winding to help stabilize speed.

The COMPOUND WOUND motor has both a shunt field winding and a comparatively heavy series winding.

VOLTAGE

Most d.c. motors on board naval vessels are designed to operate on 115 volts, or 230 volts.

FUNDAMENTALS

How well do you remember the basic principles of motor operation? Better take an inventory. Start at the beginning. What is a motor? It is a machine that CONVERTS electrical energy into mechanical energy. What makes it run? You might answer that question by saying—MOTOR ACTION results when a current-carrying conductor is placed in a magnetic field. Or you may reply, the FORCE developed by a motor is the result of INTERACTION between the magnetic field of the main poles and the magnetic field which surrounds the conductors of the armature.

You should also remember that the force of TORQUE developed by a motor is directly proportional to the strength of the main

pole flux field and the amount of current flowing in the armature. This is summed up by—

$$T = K\Phi I$$

where T is torque

K is the circuit constant

Φ is phase angle

I is current

You know that there is a GENERATOR ACTION in a motor once it starts running, and that this action causes an emf to be induced in the coils of the motor armature. This induced emf opposes the applied emf and is called counter emf. Therefore, the current flowing in the armature depends upon the difference between the applied voltage, E_a, and the COUNTER EMF, E_g, as well as the RESISTANCE, R_a, of the armature circuit—

$$I_a = \frac{E_a - E_g}{R_a}$$

The important thing to remember about counter emf is that it opposes the applied voltage and is directly proportional to the speed and field strength of the motor. $E_g = K\Phi N$.

So much for the basic principles of motor operation. Now for some of the practical problems which come up when you put these principles to work in a motor.

ARMATURE REACTION

ARMATURE REACTION—The last time you saw this term was while you were studying generators back in Chapter 5. At that time you learned that the distortion of the main flux field caused by the reaction of the main field flux and the armature flux is called armature reaction.

Figure 72 will help to remind you of the effect ARMATURE REACTION has upon the main field of a generator. The tip of one field pole is crowded with flux lines while the flux field in the other pole tip has been reduced considerably. Furthermore the electrical neutral plane has shifted forward in the direction of rotation. Except for the DIRECTION the neutral plane shifts, essentially the same thing happens in a motor.

Like the generator, the motor has two fields—the main pole field and the field around the conductors of the armature, but

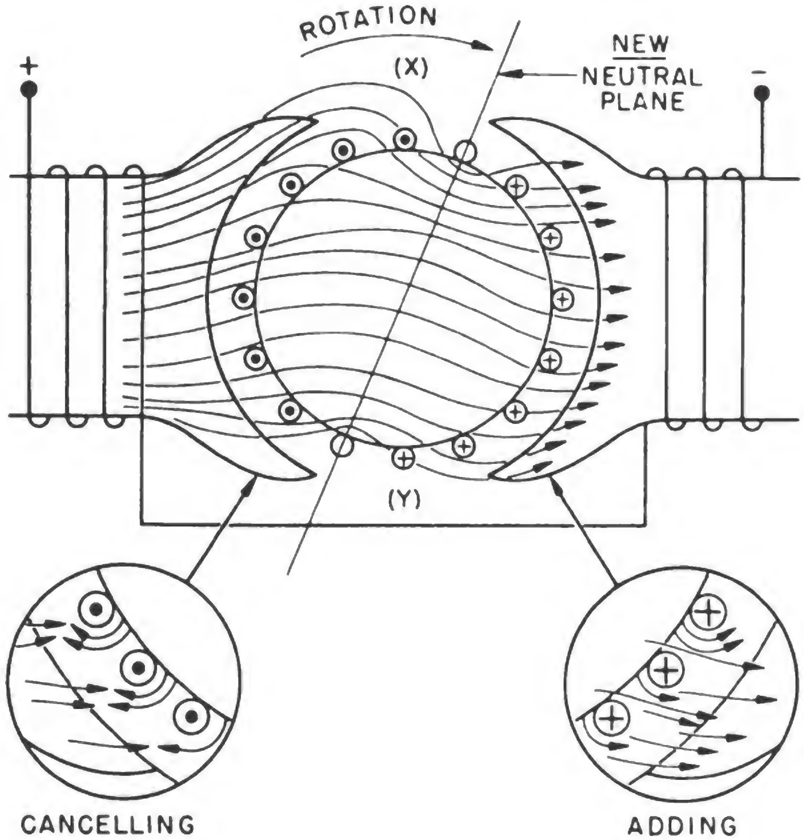


Figure 72.—Armature reaction causes flux distortion.

the RELATIVE POLARITIES of these fields are reversed as compared with the GENERATOR.

Take a look at figure 73. By using your hand rules you can show that if a motor and generator have the same field polarity and rotate in the same direction, their ARMATURE CURRENTS flow in OPPOSITE DIRECTIONS.

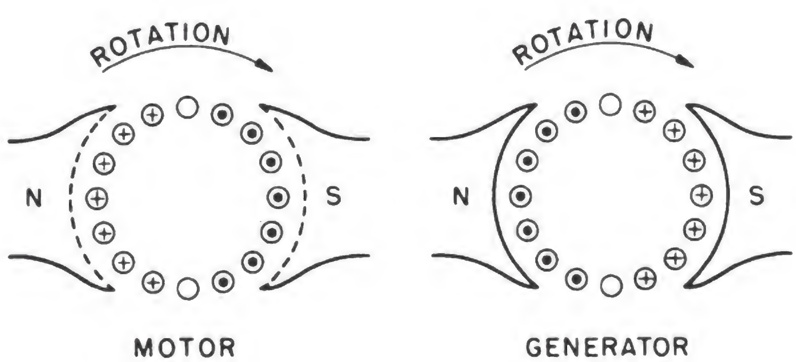


Figure 73.—Relative polarities of a motor and generator field.

Since the armature currents of the motor and generator are flowing in opposite directions, the resultant flux field must be in opposite directions. The resultant flux fields and their directions are shown in figure 74. Prove these flux fields are correct by using your hand rule for flux.

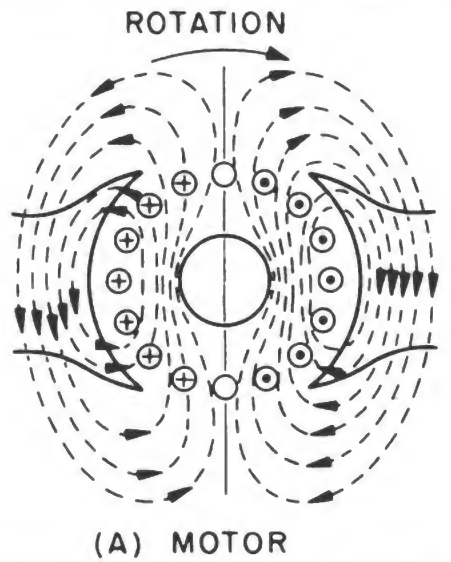


Figure 74.—Comparison of armature flux fields in a motor and generator.

Since the armature flux fields of the motor and the generator are of opposite polarities, the effect of the motor armature flux upon the main field of the motor must be the exact OPPOSITE of that which the generator armature flux has upon the main field of the generator. Figure 75 shows the resulting field

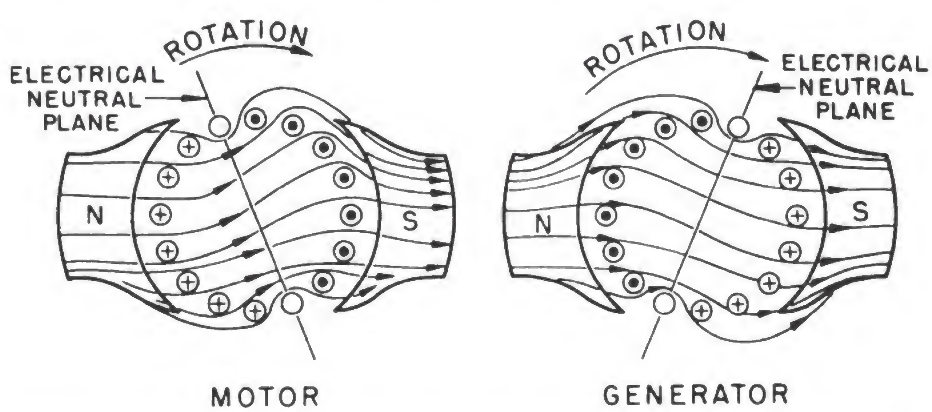


Figure 75.—Comparison of electrical neutral plane of a motor and a generator.

distortion in each case. Notice that the neutral plane of the generator has shifted FORWARD in the direction of rotation. But,

the neutral plane for the motor has shifted BACKWARD against the direction of rotation.

As in the generator, this new neutral plane for the motor is called the electrical neutral plane, and that's where the brushes go. You shifted the brushes forward in the direction of rotation in the generator but you SHIFT THEM BACKWARD AGAINST ROTATION IN A MOTOR.

D.C. MOTOR COMMUTATION

In a d.c. motor, one side of the armature coil carries current in one direction while it is under a north pole but the same coil side carries current in the opposite direction while it is under a south pole. Since the current supplied to the coil side is direct current and flows continuously in one direction, it is necessary to COMMUTE the current to the coil side. That is, the current must flow in through the coil side while it is under one pole and flow out through the coil side while it is under the other pole.

The method used for commutation in a motor is the same as the method used for commutation in a generator. And you run into the same troubles, one of which you especially remember —sparking due to self induction and armature reaction.

At the instant before a coil is short circuited by the brush, the current is flowing through it in one direction. The next instant the COMMUTATOR BARS are UNDER THE BRUSHES and the coil is short circuited. At this instant the current flowing in the coil should be ZERO. The next instant the coil lies on the OTHER SIDE of the brush and current is FLOWING IN THE OPPOSITE DIRECTION.

Notice that the current SHOULD BE zero in the coil while the coil is short circuited. Well, you know the current must go to zero before it can be reversed. But it doesn't.

Remember Lenz's law? As the current decreases to zero, a VOLTAGE is INDUCED which tends to CONTINUE THE FLOW of current in the same direction. This voltage due to self induction is very small. However the short circuited coil has a very low resistance, about .001 of an ohm, and this small voltage due to self induction will cause a LARGE CURRENT TO FLOW. Result—sparking when the commutator segments connected to the coil move out from under the brushes.

HOW TO CURE SPARKING

To overcome the voltage of self induction in a d.c. motor, you need to produce a voltage which opposes it. Remember the voltage of self induction causes the current to continue to flow in the same direction. Therefore, the emf of self induction has the same direction as the voltage applied to the coil side just before it is short circuited. To overcome this emf of self induction you need a voltage in the opposite direction to the voltage which caused the current to flow in the coil side while it was under the pole it is just leaving.

That shouldn't be too hard to figure out. Remember counter emf in a generator? Looks as if that's the voltage you need to overcome the emf of self induction.

But how are you going to use it? The coil being commuted is in the neutral plane and is cutting no flux lines. Therefore, there is no counter emf induced in the coil.

Why not SHIFT the brushes to a point where a coil does not have an induced counter emf? Which way shall you shift the brushes?

Well, you want this emf to have the SAME DIRECTION as the COUNTER EMF INDUCED in the coil while it was under the pole it is just leaving. So you shift the brushes backward against rotation.

How far are they shifted? Only to a point where the counter emf in the coil being commutated is strong enough to overcome the sparking. By shifting the brushes a little farther you help start the current flowing in the opposite direction in preparation for the main current which an instant later will flow through the coil side as it starts to pass under the other pole.

D.C. MOTOR INTERPOLES

From your study of generators you know that INTERPOLES are used to overcome this emf of self induction and at the same time partly correct armature reaction. Interpoles can also be used in motors for the same purposes. The only difference is this—in the generator, the interpole has the SAME POLARITY as the MAIN POLE AHEAD of it in the direction of rotation; but the INTERPOLE IN A MOTOR must have the SAME POLARITY AS THE MAIN POLE DIRECTLY BACK OF IT. Why?

You overcame the emf of self induction by commutating the coil while it was CUTTING the FLUX of the MAIN POLE it was just LEAVING. So, if the interpole is to overcome the emf of self induction, it must have the SAME POLARITY as THE MAIN POLE the coil is leaving. That is the POLE DIRECTLY BEHIND the interpole.

The INTERPOLE in a motor is connected to carry the armature current as in the generator. As the load varies the interpole flux varies, and it isn't necessary to shift the brushes with an increase in load. Furthermore, the electrical neutral plane is near to the mechanical neutral plane.

What effect will reversing the motor have on the interpole?

You should answer that one without any trouble, that is if you know how to reverse a motor. You know that you can reverse a motor by reversing the direction of the current in the armature. But when you reverse the current in the armature you reverse the current in the interpole and consequently its polarity. So the interpole still has the polarity of the pole behind it.

OTHER AIDS TO COMMUTATION

The other means by which poor commutation in a motor may be counteracted are the same as for the generator—LAMINATED POLE TIPS, SLOTTED POLE PIECES, and COMPENSATING WINDINGS. Just remember that in each case you want to produce the same effect as in the generator but IN THE OPPOSITE DIRECTION.

CHAPTER 8

MORE ABOUT D.C. MOTORS

SPEED REGULATION AND SPEED CONTROL

SPEED REGULATION refers to the ability of a motor to maintain its speed when load is applied.

SPEED CONTROL refers to changes in motor speed caused by some external adjustment of the motor.

Speed regulation is expressed as a percentage of the no-load speed of the motor. You find it by subtracting the full-load speed from the no-load speed and dividing the difference by the no-load speed. For example, if a motor runs at 1,800 r. p. m. at no load and runs at 1,650 r. p. m. at full load the speed regulation would be—

$$\text{Speed regulation} = \frac{1{,}800 - 1{,}650}{1{,}800} \times 100 = 8.33\%$$

The important thing to remember is that built-in characteristics of the motor are responsible for speed regulation, while SPEED CONTROL is obtained by EXTERNAL ADJUSTMENTS on the motor.

SHUNT MOTOR

The shunt motor isn't exactly a stranger to you. Among other things, you have learned to refer to it as the CONSTANT SPEED MOTOR, not because the speed is absolutely the same regardless of load, but because it changes very little between no load and full load. Now, let's find out the reason for this comparatively small speed regulation in a shunt motor.

To do this, review what happens in a shunt motor as the load increases. If the load increases, the armature current must increase in direct proportion to the load. But as the current in the armature increases the COUNTER EMF must DECREASE. Therefore, since the COUNTER EMF is DIRECTLY PROPORTIONAL to the SPEED, the speed must decrease as the load increases.

Now to determine how much the speed decreases, solve the following example. A shunt motor (figure 76) is connected

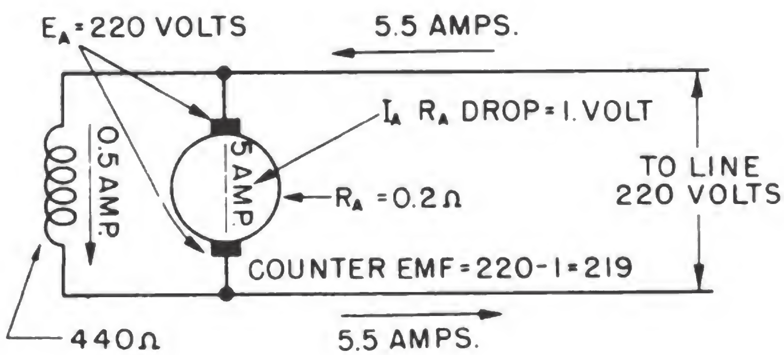


Figure 76.—Counter emf in a shunt motor at no load.

to a 220 volt line, draws 5.5 amperes, and runs at a speed of 1,800 rpm at no load. With a full load the motor draws 40.5 amperes from the line. The field has a resistance of 440 ohms, and the armature has a resistance of 0.2 of an ohm. Find the full-load speed.

Current in the field is—

$$I_f = \frac{220}{440} = 0.5 \text{ amp.}$$

Current through the armature circuit at no load is—

$$I_A = 5.5 - 0.5 = 5 \text{ amp.}$$

Counter emf is equal to line voltage minus IR drops in the armature. The IR drop in the armature at no load is—

$$I_A R_A = 5 \times 0.2 = 1 \text{ v}$$

So, the counter emf at no load is—

$$E_g = E_A - I_A R_A = 220 - 1 = 219 \text{ v}$$

IR drop in the armature at full load is—

$$I_A R_A = 40 \times 0.2 = 8 \text{ v}$$

Counter emf at full load is—

$$E_g = 220 - 8 = 212 \text{ v}$$

Thus, from no load to full load the counter emf had to drop from 219 volts to 212 volts—a very small percentage. Since the counter emf varies directly as the speed with the field held constant, the percentage of speed variation is the same as the percentage of variation in the counter emf, which is very low.

Furthermore you may set up an equation showing the direct relationship between the two speeds and the two counter emfs—

$$\frac{N_1}{N_2} = \frac{E_{g1}}{E_{g2}} \quad \text{or } N_2 = \frac{N_1 \times E_{g2}}{E_{g1}}$$

Where—

N_1 = Speed at no load
N_2 = Speed at full load
E_{g1} = Counter emf at no load
E_{g2} = Counter emf at full load

Using the equation—

$$N_2 = \frac{1{,}800 \times 212}{219} = 1{,}742 \text{ r. p. m.}$$

approximately the full-load speed.

Actually the full-load rated speed of this motor, found on the name plate, would probably be 1,750 r. p. m. Even so the example shows you the reason for the low degree of speed regulation in a shunt motor.

Oh! You want to know why you got 1,742 r. p. m. for the full-load speed, instead of 1750 r. p. m.

That's fair enough. But with a very little help you should be able to answer that one for yourself. Remember armature reaction? It weakens the main field flux. Also, since armature reaction increases as the load goes up, the main field flux is weakened and does not remain absolutely constant as you

assumed in the example. The effect is slight but it is there. Therefore the reduction in counter emf from 219 volts to 212 volts is not entirely the result of decreased speed but is caused partly by the weakened field. So, the speed drops to 1,750 r. p. m. and the remainder of the drop in counter emf is a result of the weakened field flux.

SERIES MOTOR

In a series motor the field is connected in series with the armature (figure 77). The field carries the same current as

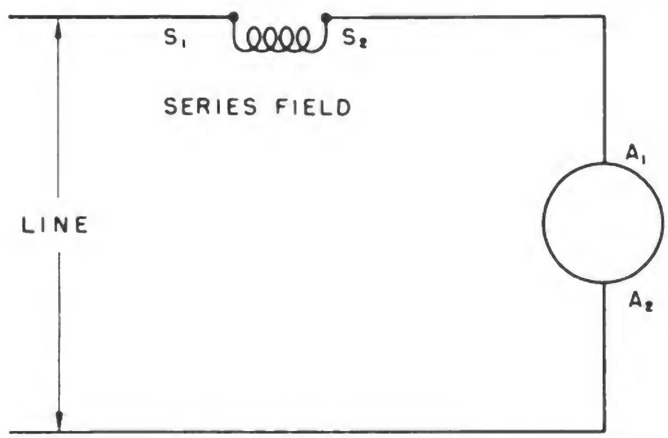


Figure 77.—A series d.c. motor connection.

the armature. That's an important point to remember—the field carries the armature current. Therefore, if the load changes the current through the armature, it also changes the current in the field.

Up to the point of saturation of the iron, the field flux is almost directly proportional to the armature current. Therefore, in the equation for torque, ($T = K\Phi I$), since Φ varies directly with I, I may be substituted for Φ, and the equation becomes—

$$T = KI^2$$

Again, T stands for torque, K is a circuit constant, and I is the armature current.

Thus in a series motor the torque is proportional to the SQUARE of the armature current. Doubling the armature current results in quadrupling the torque. For example, if the torque is 40 lb.-ft. at 25 amperes, at 50 amperes the torque would be 160 lb.-ft. From this example you can see that the torque rises very rapidly as current increases.

This characteristic of a series motor makes its use very desirable where a HIGH STARTING TORQUE is needed. At the time of starting, before the motor has built up any counter emf, the current is high and the resulting torque is very high at the time it is most needed.

Just to keep the records straight, it should be pointed out that the armature reaction and saturation of the iron both tend to prevent the torque from increasing as rapidly as the square of the current. This fact can be seen in the torque curve for a series motor, shown in figure 78. If you check the torque at five amperes, you find it to be 3.5 lb.-ft. But at 10 amperes the torque is 12 lb.-ft. instead of 14 lb.-ft., which it would have been if it were not for the saturation of the iron and armature reaction.

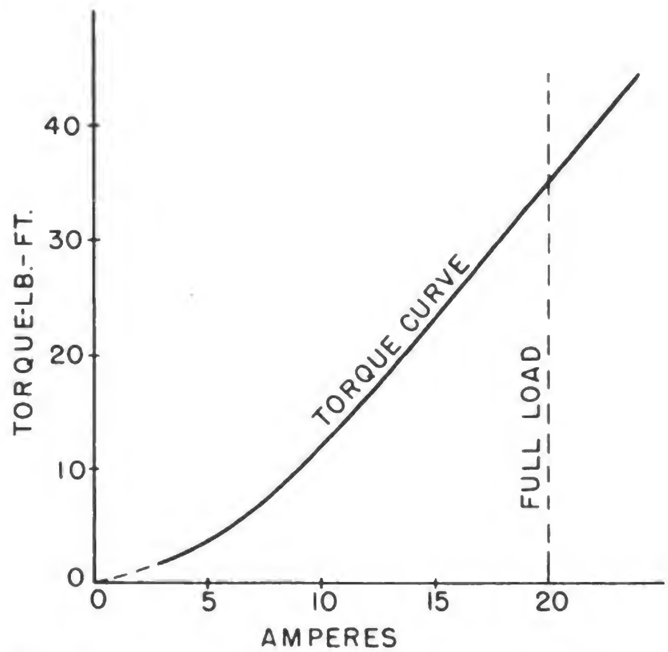


Figure 78.—Torque curve for a series d.c. motor, 5 hp., 230 volts.

So much for torque. How about the speed of a series motor? How is it going to be affected by this varying field flux?

You know that if the load goes up, the current goes up. To allow this additional current to flow in the armature, the motor counter emf must go down, according to the equation

$$I_A = \frac{E_A - E_G}{R_A}$$

where E_A, the applied voltage, and R_A are constant. If, and that is a BIG IF, the field flux remained constant, the necessary

decreases in counter emf could be accomplished by a slight decrease in speed, as in the shunt motor. The flux, however, does NOT remain constant. It increases almost proportionally to the armature current. That is, if you double the load you almost double the field flux. Hence the speed must decrease still further to make up for this increase in flux. To illustrate this point, solve the following example.

A 5 hp., 110-volt, series d.c. motor is running at 1,050 r. p. m. when the current is 5 amperes. The resistance of the armature, including brushes, is 0.4 ohm, and that of the series field is 0.6 ohm.

First, suppose that the field is constant, and calculate the speed when the machine is carrying 15 amperes.

The total resistance is

$$R = 0.4 + 0.6 = 1 \text{ ohm}$$

The counter emf with five amperes is

$$E_g = 110 - (1 \times 5) = 105 \text{ volts}$$

The counter emf with 15 amperes is

$$E_g = 110 - (1 \times 15) = 95 \text{ volts}$$

Therefore, if the flux were constant, the speed at 15 amperes would be

$$\frac{95 \times 1{,}050}{105} = 950 \text{ r. p. m.}$$

But the field isn't constant. This is a series motor and the field flux increases with the load. Suppose the flux at 15 amperes is twice as much as at five amperes. It won't be three times as much because of saturation of the iron and armature reaction. The SPEED MUST DROP BELOW 950 r. p. m. to make up for this increase in flux. We can calculate the speed change by using the equation for counter emf—

$$E_g = \text{K}\Phi\text{N}$$

When the current is five amperes, the speed is 1,050 r. p. m., and the counter emf is 105 volts. Substituting in the equation—

$$105 = \text{K} \times \Phi \times 1{,}050$$

When the current is 15 amperes, the flux is doubled, and the counter emf is 95 volts. The equation now becomes—

$$95 = \text{K} \times 2 \times \Phi \times \text{N}$$

We can solve for the new speed, *N*, by setting up a direct proportion problem—

$$\frac{105}{90} = \frac{K \times \Phi \times 1{,}050}{K \times 2 \times \Phi \times N} = \frac{1{,}050}{2N}$$

$$N = \frac{95 \times 1{,}050}{2 \times 105}$$

$$N = 475 \text{ r. p. m.}$$

This problem shows that when the current in this series motor increases from 5 to 15 amperes, the field flux is doubled. And in order to decrease the counter emf enough to allow the 15 amperes to flow, the speed decreases from 1,050 to 475 r. p. m.

On the other hand, as the load on a series motor decreases, the field flux decreases and the motor speed must go up to generate the required counter emf. So, when there is no load on the series motor and the field flux is very low or almost zero, the speed rises to a point where it is dangerous. The motor may run so fast that the armature coils are thrown out of the slots and the motor is wrecked.

Because of the fact that an unloaded or lightly loaded series motor may run away and wreck itself, it is never connected to a load through a belt. Instead, a series motor is always connected to its load by a shaft or gears. It is used chiefly for widely varying load, when extreme speed changes aren't objectionable, and when the operator is always present.

COMPOUND WOUND D.C. MOTORS

The usual connections for a compound wound d.c. motor are shown in figure *79A*. The series field is so connected that it aids the shunt field. With this type of connection, the motor is known as a CUMULATIVE COMPOUND MOTOR. The field strength increases as the load increases.

In figure *79B*, the fields are so connected that the series field OPPOSES the shunt field. When connected in this manner the motor is known as a DIFFERENTIAL MOTOR. As the load increases the field strength decreases. This connection is used

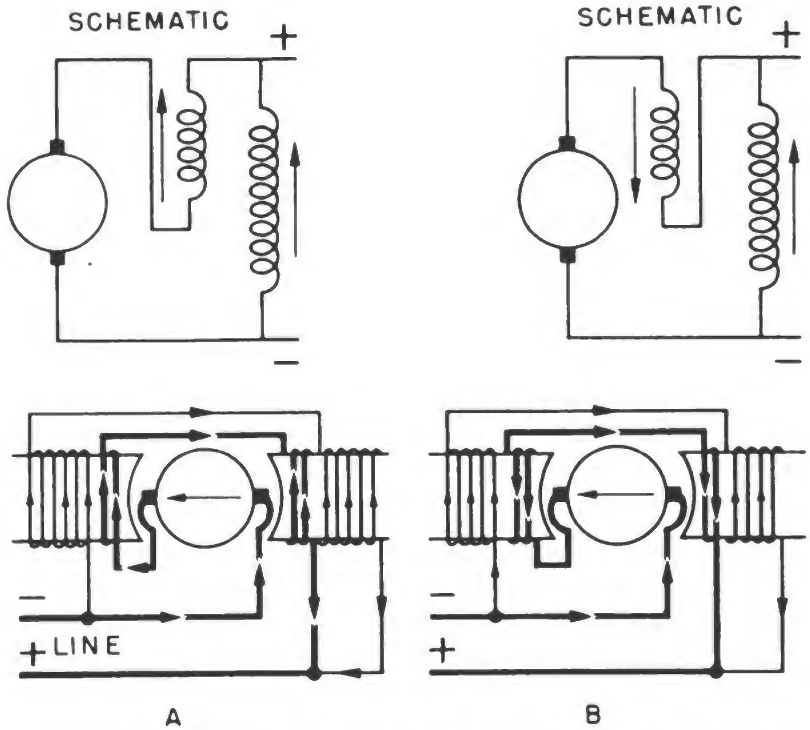


Figure 79.—Connections for a compound wound, d.c. motor

so seldom that the term COMPOUND MOTOR is generally understood to mean a CUMULATIVE COMPOUND motor, and that is the way it will be used throughout this manual.

Since the compound motor has both a shunt and a series field, you would expect its characteristics to be a COMBINATION of the series and shunt motor characteristics. Well, they are not exactly a combination—but a compromise between the two.

The speed of the compound motor varies more than the speed of the shunt motor, because as the load increases the field flux increases. On the other hand, when the load is removed and the series field flux is practically zero, it doesn't run away as the series motor does, because the shunt field gives it a definite no-load speed. Thus the entire load may be removed without danger to the motor.

The SPEED REGULATION of a compound motor is dependent upon the relative strength of the series and shunt fields. A compound motor with a strong shunt field and a weak series field will have a speed regulation similar to a shunt motor. If the series field is comparatively strong, the speed regulation will be greater than for the shunt motor and the torque characteristics will more nearly approach that of the series motor.

TORQUE CHARACTERISTICS OF A COMPOUND WOUND D.C. MOTOR

The starting torque of a compound motor will be where you would expect it—somewhere between that of the shunt motor and the series motor. It is higher than the starting torque of the shunt motor but not quite as high as the starting torque of the series motor. And, as in speed regulation, the relative strength of the series and shunt fields will determine whether the starting torque is nearer the starting torque of the shunt or series motor.

Here is a good place to get something straightened out. During all these comparisons of starting torque for different motors, remember this—a compound motor, a shunt motor, and a series motor which have the same horsepower rating DEVELOP EXACTLY THE SAME-FULL LOAD TORQUE.

When you say the series motor has a higher STARTING TORQUE than a shunt motor of the same horsepower, you mean that the series motor requires less current than the shunt motor to produce the torque necessary to start a load.

To start with a full load, the SHUNT MOTOR will ordinarily require 1.5 times full-load current, while a series motor will require only 1.3 times full-load current. The starting current for the compound motor will be somewhere between 1.5 and 1.3 times full-load current, depending upon the relative strength of the series and shunt fields.

The extra starting torque developed by the series motor results from the rapid torque increase when the current goes above full-load current. Actually, below full-load current the torque of a series motor is lower than the torque of the same size shunt motor carrying the same current. Now that isn't a hard statement to understand if you remember just three things—

First, the torque equation, $T = K\Phi I$.

Next, the field of the shunt motor is full strength regardless of the load current.

And finally, you know the field of the series motor doesn't reach full strength until full-load current is flowing.

Thus, for a given armature current below full-load value, the torque of a series motor will be less than the torque of a shunt

motor of the same size. The torque of a series motor increases much faster, however, almost as the SQUARE of the current, while the torque of a shunt motor increases DIRECTLY with the current.

The degree to which these characteristics apply to the compound motor depend upon the relative strength of the series and shunt fields.

The starting torque and speed characteristics of the compound motor make it desirable for use where the starting load is heavy and a comparatively steady and high running speed is necessary.

The differential motor may be made to operate with a more nearly constant speed than the shunt motor, but the starting torque will not be as high. The speed is more nearly constant than the shunt motor speed, because as the load increases the series field becomes stronger, thereby weakening the shunt field. In other words, as the load increases the total field strength is decreased. Thus the reduction in counter emf, which is necessary to allow the increased current to flow, is brought about by a reduction in field flux instead of a reduction in speed. By making the series field strong enough—that is, with a sufficient number of turns—it is possible to make the speed almost constant from no load to full load, or even cause it to go up as the load is applied.

Of course there is a limit to the number of turns which may be put on the series field. Here's what could happen if it has too many turns. At starting, when the current is very high, the series field may be equal in strength to the shunt field, and their total flux may become zero. Or course the motor wouldn't start, because no counter emf would be generated. The current would go higher. The series field would become stronger than the shunt field and start the motor in the REVERSE direction. You can see the danger which could result from something like this. To prevent this, some differential motors have short circuiting switches which short out the series field at the time of starting.

If a differential motor with a strong series field is TOO HEAVILY OVERLOADED, it will STOP or REVERSE its direction of rotation because when the load is increased to a point where

the ampere-turns in the series field equal the ampere-turns in the shunt field the total field flux becomes zero. As a result no counter-emf is generated, and the current goes very high. The series field strength becomes greater than the shunt field forcing the motor to reverse. Generally, the motor doesn't reverse, it stops. When this happens, the current through the armature and series windings will go high enough to burn out these windings.

Figure 80 shows a comparison of the torque and speed-load characteristics of the shunt, series and compound motors.

The torque curve for the shunt motor is a straight line because the field remains constant and the torque varies directly with the armature current. However the curves for the series and compound motor show that below full load the torque of neither the series nor compound motor is as high as the torque of the shunt motor. That is because the field strength of neither the series or compound motor reaches its full value until full-load current is flowing.

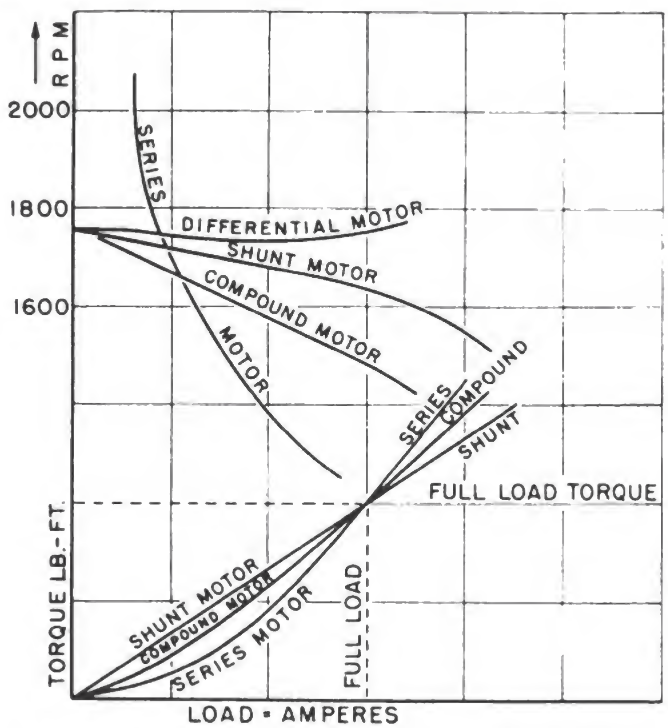


Figure 80.—Performance curves of series, shunt and compound wound d.c. motors of same horsepower.

But wait—you are saying the compound motor has a shunt field just as has the shunt motor. That's the truth, but not the

whole truth. The compound motor does have a shunt field, but the shunt field of a compound motor doesn't have as many ampere-turns as the field of a shunt motor with the same horsepower rating. If a compound motor and a shunt motor have the same horsepower rating, with full-load current flowing, the total ampere-turns of the series and shunt fields in the compound motor will be equal to the ampere-turns of the field in the shunt motor. Thus there is a difference in strength between the two shunt fields which is equal to the strength of the series field when full-load current is flowing. That is a good point to remember when you are comparing the performance curves of the different motors.

The speed-load curves of the shunt motor and the compound motor are almost a straight line from no load to full load. However, the speed-load curve for the series motor doesn't begin to flatten out until it reaches a point near full load, when the field iron is nearing its saturation point for flux.

SPEED CONTROL

The speed of a SHUNT MOTOR which is driving a definite load can be varied by changing either the field flux or the voltage applied to the armature. This follows from the equation

$$I_A = \frac{E_A - E_g}{R_A}$$

where I_A is armature current at a definite load, E_A is the voltage applied to the armature terminals, E_g is the counter emf, and R_A is the armature resistance. And from the equation

$$E_g = \mathrm{K}\Phi\mathrm{N}$$

where E_g is counter emf, K is the circuit constant, Φ is field flux, and N is speed.

If the load requirements are such that the armature current is constant, then according to the first equation, where E_A is constant, E_g must remain constant. Therefore, by the second equation the speed must change inversely with the field flux. That is, if Φ goes down, N goes up in order to keep E_g constant. Thus the speed of a shunt motor increases when field flux decreases, and the speed decreases when field flux is increased.

METHODS OF OBTAINING SPEED CONTROL

The most common method used to vary the strength of the field flux is to put a variable rheostat in series with the shunt field winding, as shown in figure 81. A 24-percent adjustment

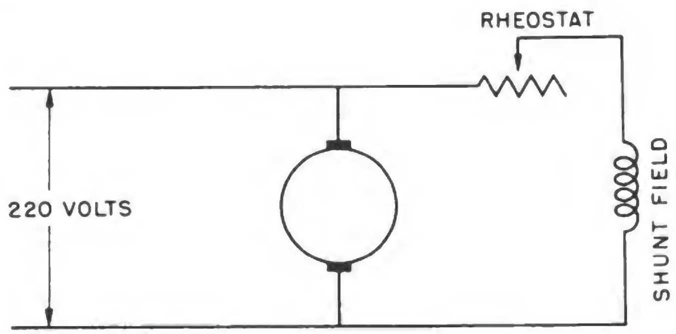


Figure 81.—Speed control by using a variable resistor in series with the shunt field.

of speed by this method is about all that is practical on the ordinary shunt motor. However, especially designed motors may give a 6 to 1 variation between maximum and minimum speeds.

From this discussion, you can see that a field rheostat cannot be used to decrease the speed of the motor below the normal rated speed, and for that reason it is often referred to as SPEED CONTROL ABOVE NORMAL.

Now, let's see what happens when the voltage applied to the armature terminals is reduced.

If a rheostat is placed in series with the armature of a shunt motor (figure 82), the speed would be varied because the voltage across the armature terminals would be changed. But notice that the rheostat is not in series with the shunt field. Therefore, the shunt field remains constant, except for the small variation due to armature reaction. If I_A is constant, then by the equation

$$I_A = \frac{E_A - E_g}{R_A}$$

E_g is going to vary with E_A. Also from the equation

$$E_g = K\Phi N$$

if Φ is constant, the speed is proportional to E_g. Therefore, if Φ is constant and I_A is constant, the speed will be proportional

to E_A, the voltage applied to the armature terminals. Remember the voltage applied to the armature terminals is equal to the line voltage less the voltage drop across the rheostat.

For example, in figure 82, if the load current is 40 amperes and the resistance cut into the rheostat is 2.5 ohms, the voltage drop across the rheostat is 100 volts ($40 \times 2.5 = 100$, and the voltage applied to the armature terminals is 120 volts ($220 - 100 = 120$).

The following example is a good illustration of how the armature method of speed control may be used. Go through the solution step by step until you are certain you know exactly why each calculation is made.

A 10 hp., 220 volt, shunt motor running at 1,800 r. p. m. takes an armature current of 50 amperes and a field current of 0.35 amperes. The armature resistance, including the brushes, is 0.4 ohm. How much resistance must be inserted in the armature circuit to reduce the speed to 900 r. p. m. with the same armature current?

Here is the solution—

The voltage drop in the armature circuit is

$$I_A R_A = 50 \times 0.4 = 20 \text{ volts}$$

The counter emf at 1,800 r. p. m. is

$$E_g = E_A - I_A R_A = 220 - 20 = 200 \text{ volts.}$$

The counter emf at 900 r. p. m. is

$$200 \div 20 = 10 \text{ volts.}$$

Thus the voltage drop across the armature terminals at 900 r. p. m. is

$$10 + 20 = 30 \text{ volts.}$$

Therefore the resistance must be sufficient to consume the remainder of the line voltage, or

$$220 - 30 = 190 \text{ volts.}$$

The current through the resistance is the armature current 50 amperes, so the resistance R_X of that rheostat is

$$R_X = \frac{190}{50} = 3.8 \text{ ohms.}$$

Since by armature control the motor cannot be made to exceed its normal rated speed, it is often referred to as SPEED CONTROL BELOW NORMAL.

When the speed of a shunt motor is adjusted by armature

control, the speed regulation becomes very poor at the lower speeds. Also there is a power loss, across the rheostat equal to I^2R. For these reasons, field control is more generally used.

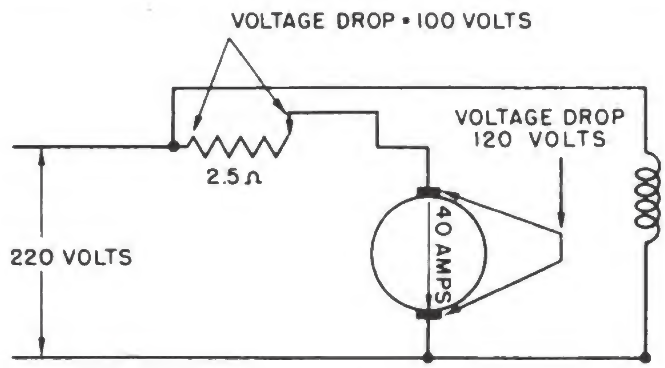


Figure 82.—Speed control by using a variable resistor in series with armature.

Armature control is used only where an occasional decrease in speed is required, or where the load decreases with the speed as in blowers and fans.

SPEED CONTROL IN SERIES WOUND D.C. MOTORS

A series motor may have its speed for a particular load changed by armature control, using a series resistance. Increasing the resistance decreases the speed the same as it does in a shunt motor, because the series field is constant with a constant armature current. Also, the speed may be increased by field control. There are two ways of doing this. The field flux may be decreased by shunting off a portion of the current as shown in figure 83*A*. When a portion of the current is shunted around the series field, the field flux becomes weaker

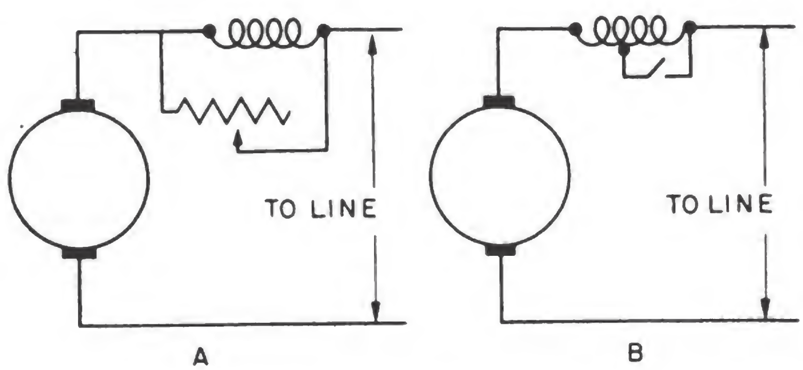


Figure 83.—Field control of speed in a series wound d.c. motor.

and the speed has to go up to generate the required counter emf. The same effect may be obtained by cutting down the number of turns through which the series field current must flow. Figure 83*B* shows how a number of turns may be shunted out of the series field. However, in series motors armature control is generally used.

SPEED CONTROL IN COMPOUND WOUND D.C. MOTOR

The speed of a compound motor may be adjusted by EITHER armature control or field control. The method in either case is the same as that used in the shunt motor. Here again the FIELD CONTROL method is MORE EFFICIENT and most generally used. Unless the motor is especially designed the speed adjustment does not exceed 25 percent. Where separately excited motors are used for propulsion on Naval vessels they are designed to operate over a wide range of speed and the armature control is often used. But instead of placing a rheostat in series with the armature, the field is separately excited from a constant source and the voltage to the armature is adjusted by varying the output of the generator.

CHAPTER 9

STARTERS AND CONTROLLERS FOR D.C. MOTORS

WHY USE THEM?

Have you ever tried to operate an automobile that had no starter, steering gear, clutching mechanism, reverse gear, or brakes?

Sounds absurd, doesn't it?

Well, it is. But no more absurd than trying to operate an electric motor without some provision for controlling it. If you have electric energy available and you want to use it to drive the propellers of a ship, what do you do? You use a motor to convert the electric energy to mechanical energy.

But how about starting, stopping, reversing, and changing the speed of the motor? This is where the controllers come in—to control the operation of the motor. The manner in which a controller works depends on the type of motor and the job it is to do. Controllers range from the simple fused line switch to large mechanisms which will start, stop, reverse, and control the speed of a motor at the touch of a button.

Controllers are equipped with safety devices for the protection of the operators, motors, and the electric circuit.

TYPES OF CONTROLLERS

There are five distinct types of controllers with reference to the degree of enclosure of the control mechanism.

The OPEN TYPE is not provided with any enclosure. The SEMIPROTECTED TYPE has its resistors, connections, and so forth mounted on the rear of a panel underneath a protected enclosure. The front of the panel is not enclosed. In the PROTECTED TYPE, the entire controller is contained within an enclosure. The DRIPPROOF TYPE may be any one of the three types already mentioned, but in addition it is provided with protection from falling solids or liquids. The WATERPROOF TYPE is enclosed in a solid case. All fittings are gasketed and it is completely protected against water from the weather or a stream from a hose.

Location will largely determine which of these types will be used.

CLASSIFICATION

The different types of controllers are also classified according to their construction and principles of operation.

The ACROSS-LINE SWITCH is a simple fused line switch. It is used to start and stop small motors, and may be open or closed without using a starting resistance.

The FACE-PANEL type controller consists of a flat insulated panel upon which are mounted stationary contacts and a movable contact arm. The stationary contacts are usually mounted in the arc of a circle. The movable contact arm is mounted upon a pivot. The manual starter box, figure 84, is an example of the face-panel type of controller.

The DRUM CONTROLLER has for its main element a drum which can be rotated by a crank or handle. Copper segments are mounted on the drum. By rotating the drum, these copper segments can be brought into contact with stationary contacts in the form of fingers held against the copper segments by springs (figure 85). Different positions of the drum bring different segments in contact with the fingers, thus making or breaking circuits.

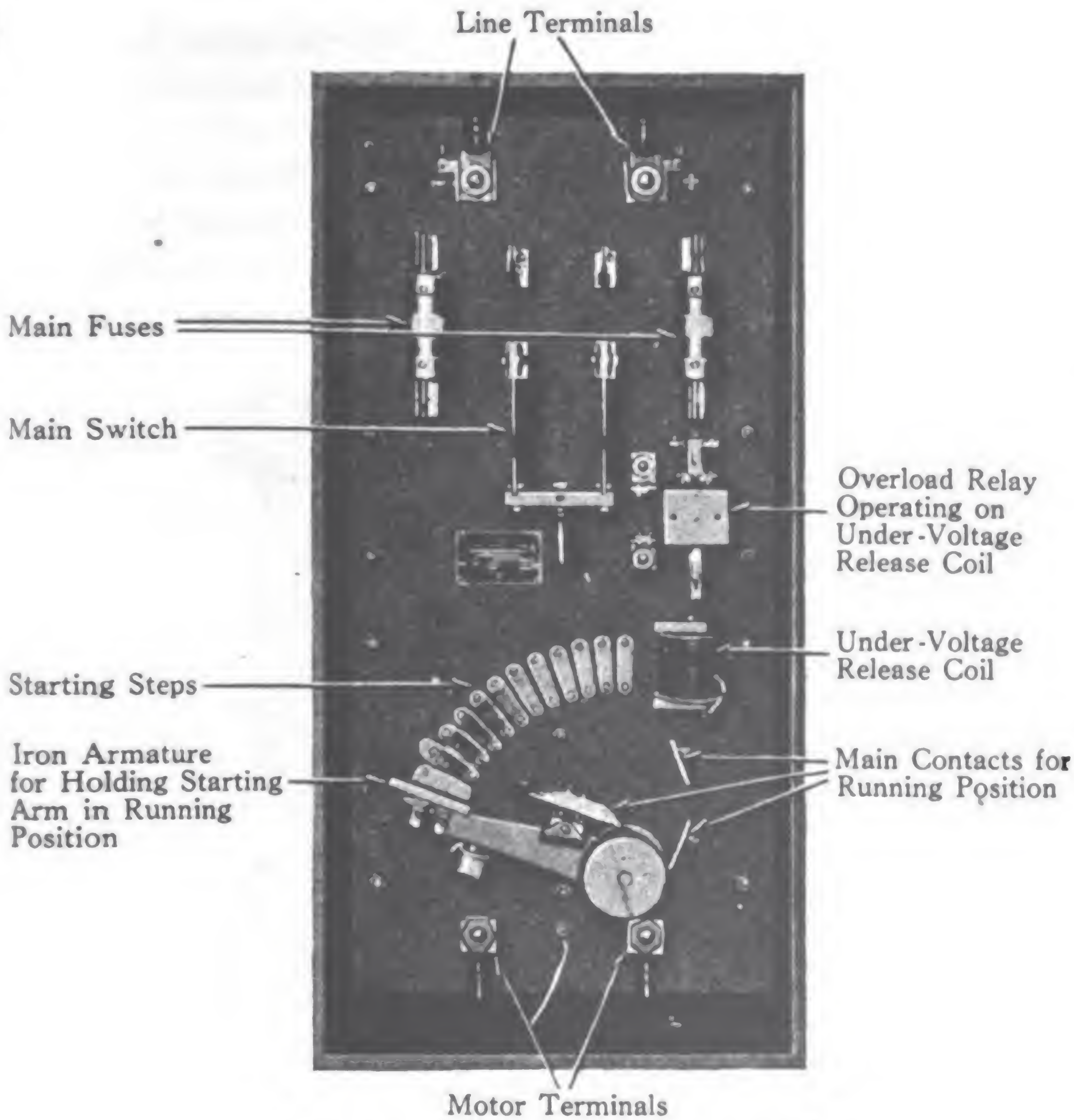


Figure 84.—Face-panel type motor controller.

The DRUM SWITCH makes and breaks circuits mechanically by cams as illustrated in figure 86. Several cams of the type shown in this figure may be mounted on one shaft and arranged to open or close different switches at different positions of the cam shaft. The cam shaft may be rotated by hand or a motor.

The PNEUMATIC CONTACTOR CONTROLLER makes and breaks circuits by separate switches controlled by air pressure.

The MAGNETIC CONTACTOR CONTROLLER is a device in which the circuits the made and broken by electromagnetic contactors. An electromagnetic contactor is ordinarily referred to as a magnetic contactor. This magnetic contactor is nothing more than a switch operated by a solenoid. You are familiar with

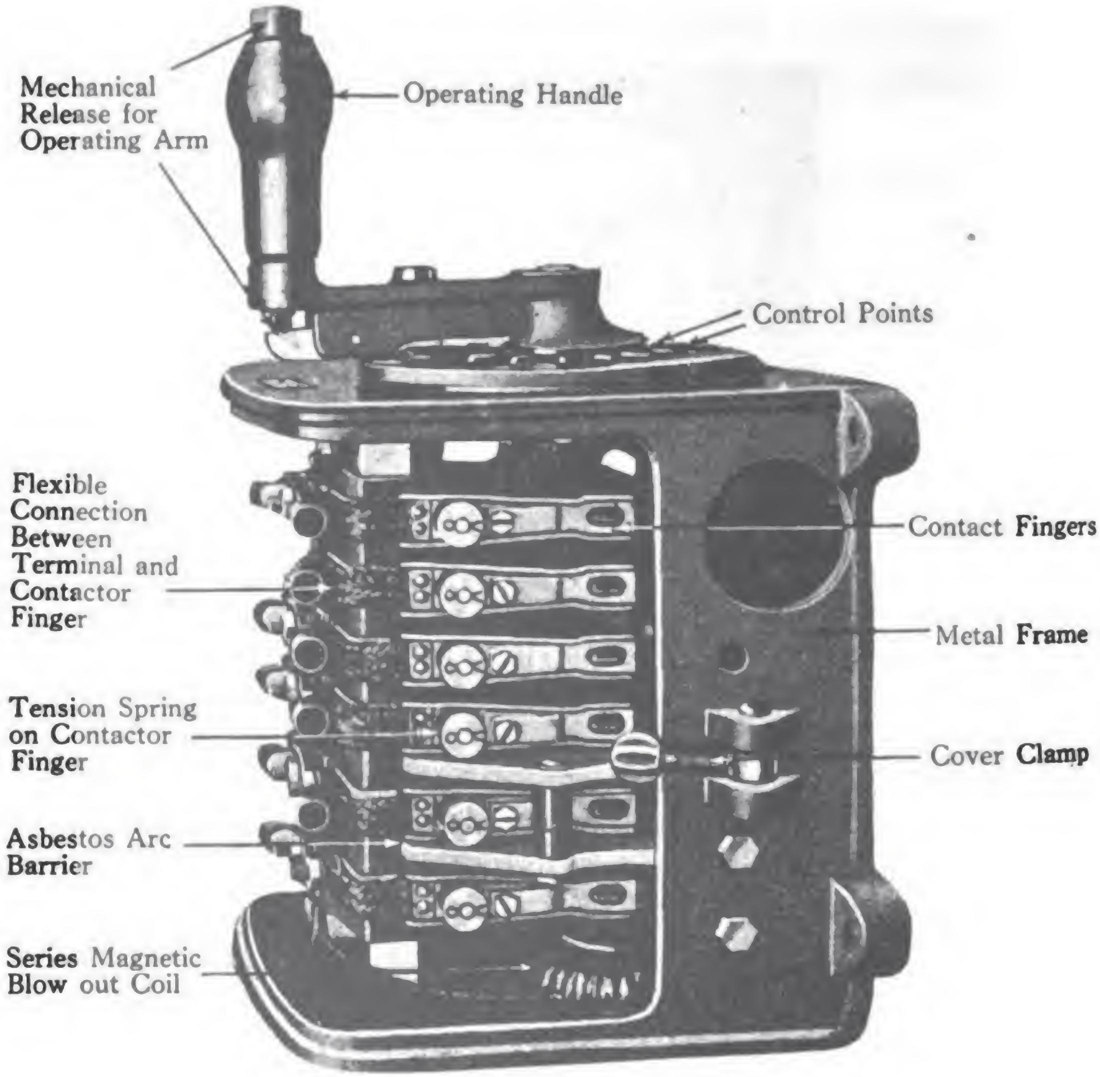


Figure 85.—Drum type controller.

the operation of solenoids, so keep that in mind while studying magnetic contactors.

These magnetic contactors, or solenoid switches, are controlled by a master switch, which may be anything from a push button to a photoelectric cell and may or may not be mounted upon the controller panel. In fact, there may be more than one switch, thus making it possible to control the motor from several different places and at a considerable distance from the controller and motor.

The MASTER SWITCH used with the magnetic contactor controller may be—

A DRUM CONTROLLER

A CAM CONTACTOR

A DRUM SWITCH
A LEVER SWITCH
A PUSH BUTTON
AN AUTOMATIC SWITCH (float, pressure gauge, etc.)

The magnetic contactor controller may be NON-AUTOMATIC, SEMI-AUTOMATIC, or FULL AUTOMATIC.

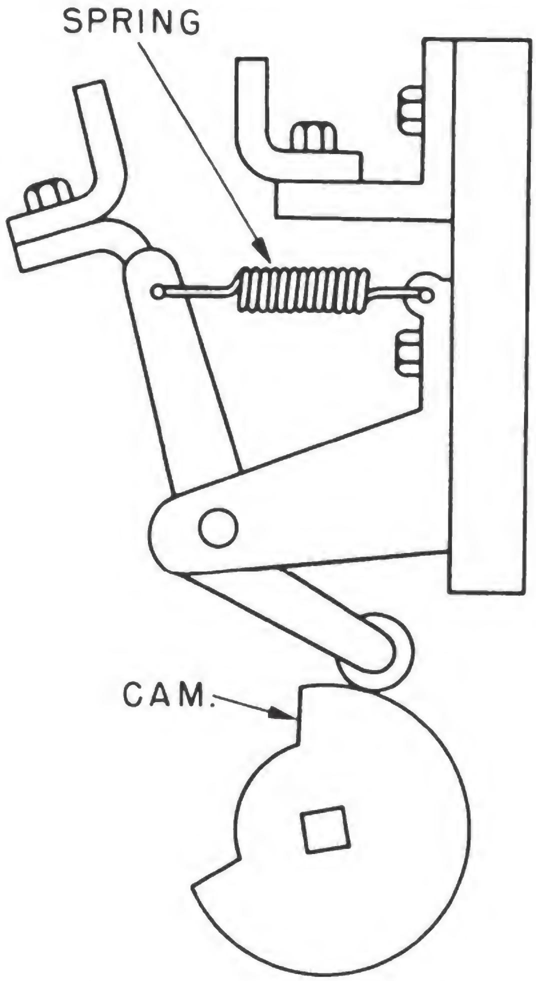


Figure 86.—Cam type controller.

If it is nonautomatic, the operator is responsible for starting, stopping, and accelerating the motor. Its master switch is usually of the drum controller or face-panel type.

In semiautomatic controllers, starting and stopping is controlled by the operator. But the rate of acceleration, that is, how fast the starting resistance is cut out, is not controlled by the operator, but by ACCELERATING CONTACTORS. The rate of acceleration of these contactors may be adjusted. But this ad-

justment is usually made by the manufacturer so that the controller will meet the requirements of the motor with which it is to be used. So don't tamper with them.

Semiautomatic controllers are usually provided with a master drum switch, a lever switch, or a push button.

With the full automatic controller, starting, stopping, speed control, and reversing are performed by the controller, after it has once been energized.

CONTROLLER TERMINAL MARKINGS

Before you begin studying the circuits, connections, and operating principles of various controllers, review the letters used to designate different terminals.

Line	L_1, L_2
Armature	A_1, A_2
Shunt Field	F_1, F_2
Series Field	S_1, S_2
Pilot Circuit	P_1, P_2
Brake	B_1, B_2
Clutch	C_1, C_2
Armature Resistance	R_1, R_2
Field Resistance	V_1, V_2

When any two of these circuits are joined at the same terminal, a combination of the proper letters is used, such as F_1 S_1 or B_2 C_2.

FACE-PANEL CONTROLLERS

The most common face-panel controllers are the manually operated starters and field rheostats with which you became familiar while studying for EM3c. Although you have already studied the principle of operation of manually operated starters, it might be a good idea to go over the main points again.

Figure 87 shows the starter arm in the OFF position. If a motor were connected to the starter, neither the field nor the armature would be energized. But when the starter arm is moved to the first contact, the shunt field is energized. Also the circuit is completed through the armature and the starting resistance in series with it. As the starter arm is advanced to the succeeding contacts mounted on the face of the

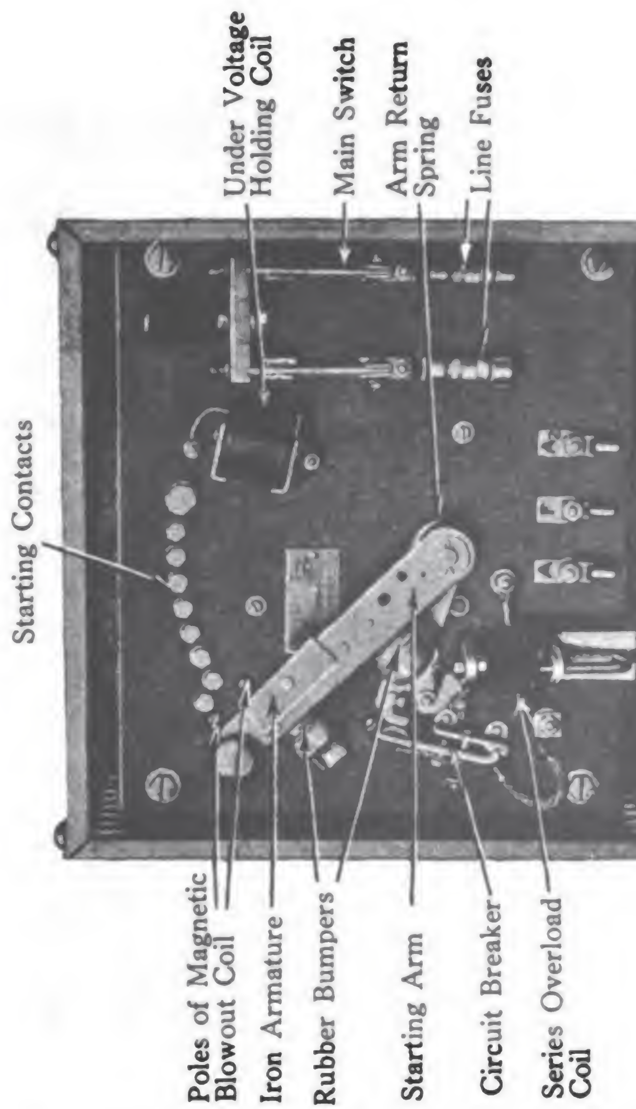


Figure 87.—Manual starter, face plate type.

starter, the resistance is gradually cut out of the armature circuit. This operation should take about 30 seconds. During the 30 seconds, the motor will build up enough counter emf to limit the current to a safe value.

When the starter arm has been moved across all the contacts, all the starting resistance has been CUT OUT, and it is in RUNNING position. The starter arm is held in RUNNING position by the magnetic attraction the LOW VOLTAGE COIL has for the iron armature secured to the starter arm. At any contact back of the RUNNING position, the starter arm will not be held by the holding coil. If it should become stuck or wedged between the OFF and RUNNING positions, a part of the starting resistance would … y short time.

The low voltage coil, or holding coil, is connected in series with the shunt field. So if the field circuit opens or the voltage drops so low there is danger of the motor running away, the starter arm is released from the holding coil and returned to the OFF position by the arm return spring. This is called LOW VOLTAGE PROTECTION.

This starter also has a CIRCUIT BREAKER, which automatically opens the circuit if the motor is too heavily overloaded or for any other reason draws too much current from the line. The circuit breaker is automatically tripped by a plunger in the SERIES OVERLOAD COIL, which is set to move the plunger when the motor current exceeds a safe value.

The starter shown in figure 88 is similar to the starter shown in figure 87. But in addition to the regular features, it has

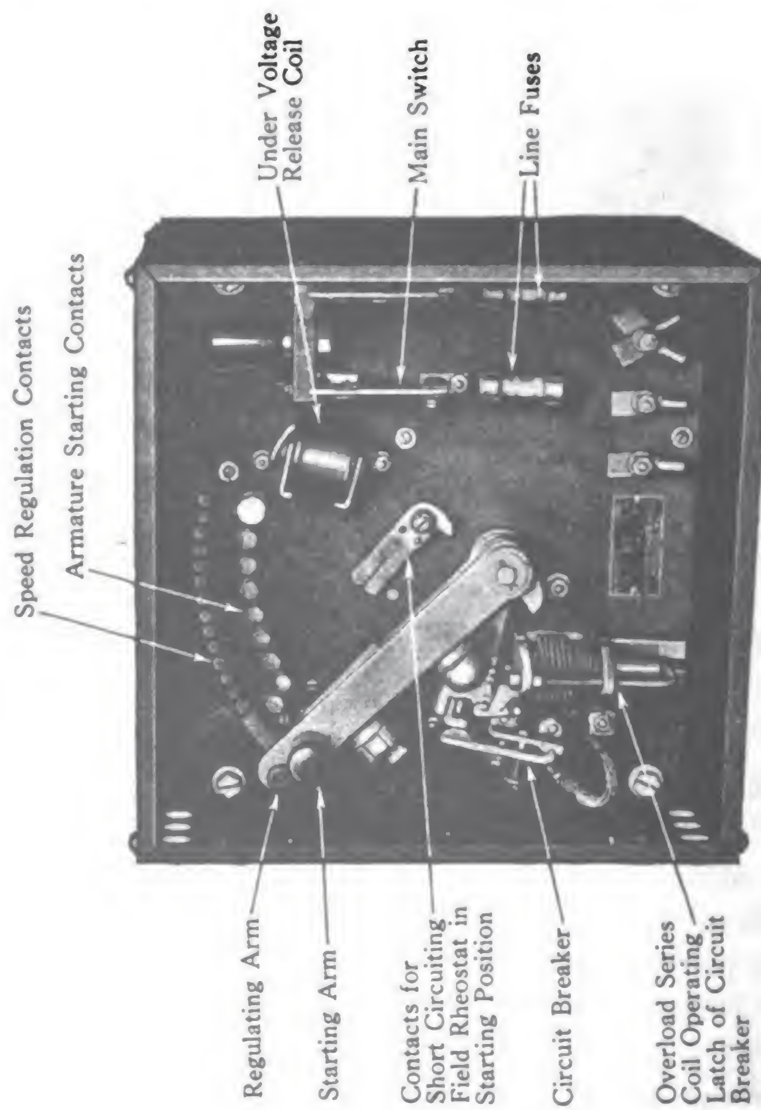


Figure 88.—A manual starter with speed control contacts.

another row of contacts. These contacts are connected to a field rheostat for use in controlling the speed of the motor.

The starter arm is held in the RUNNING position by the holding coil, but the regulating arm can be moved across the regulating contacts to cut resistance in or out of the field circuit.

The motor needs its full field strength while starting. $T = K\Phi I$. Remember? So a switch to short out the field rheostat is placed on the face of the starter.

On the face of each starter you see a fused line. NEVER CLOSE THIS SWITCH UNTIL THE STARTER ARM IS IN THE OFF POSITION.

The motor is always STOPPED by opening the LINE SWITCH.

BLOWOUT COIL

You probably noticed on the face of the starter in figure 87 an object that looks like two contacts; the ends were labelled POLES OF MAGNETIC BLOWOUT COIL. If you didn't, take another look at figure 87.

The BLOWOUT COIL is an essential part of all contactors which break circuits carrying a heavy current. Controllers are operated frequently; and each time a contactor opens, an electric arc is formed across the contactor. Unless some means is provided to extinguish this arc, the contacts soon become burned and pitted.

But by using the magnetic blowout, these arcs are moved out to the tips of the contacts and blown out. Furthermore, these contact tips are made of materials which are more resistant to the heat from the arc than the contact itself. The tips are removable and much less expensive than the main contacts.

How is the magnetic blowout constructed, and how can it extinguish an arc?

The blowout coil consists of a few turns of heavy wire wound around a small iron core. The poles of the U-shaped iron core are placed on either side of the contacts where the circuit is broken. The winding of the blowout coil is connected in the line and carries the line current. Thus, there is a strong magnetic field at the exact point where the circuit is broken and the arc is formed.

An electric arc is forced out of a magnetic field just as a current-carrying conductor is forced out of a magnetic field. Remember that the direction a current-carrying conductor moves

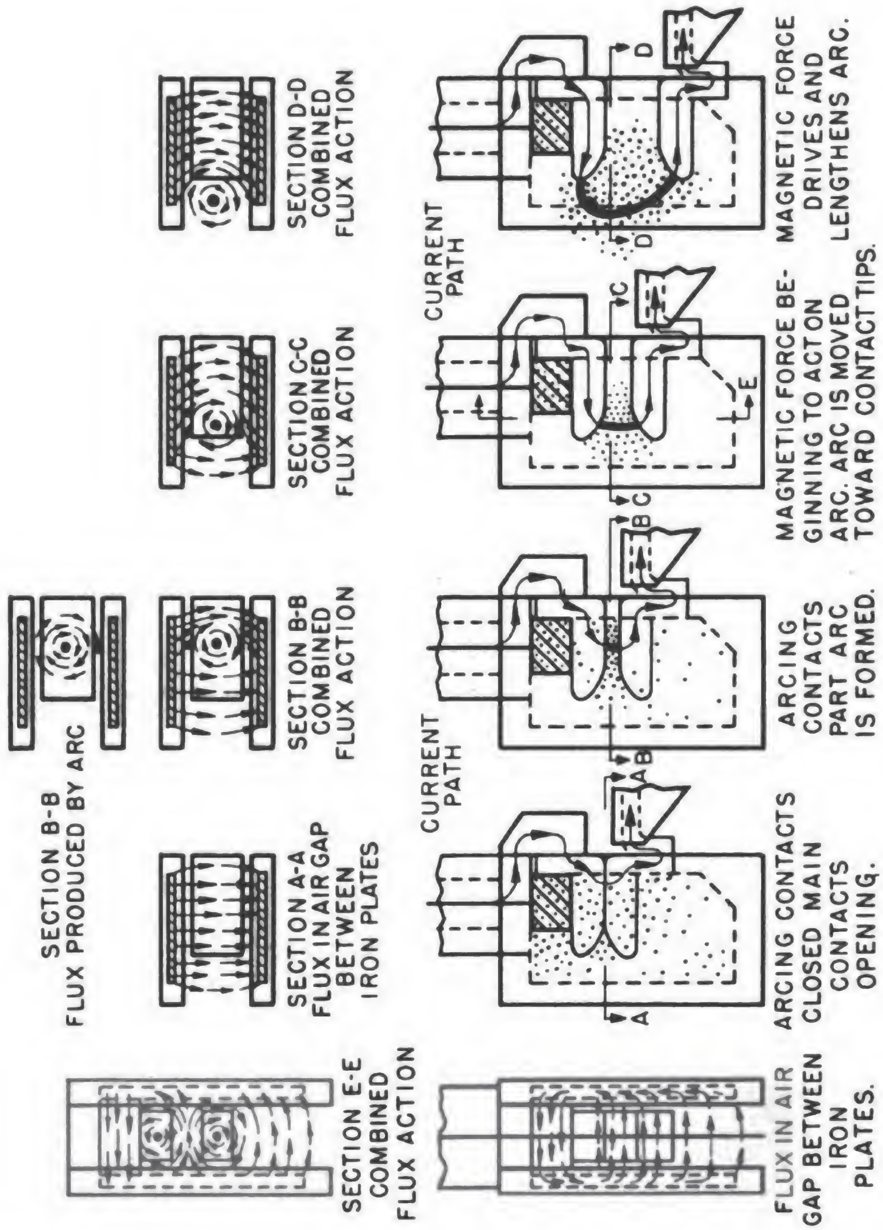


Figure 89.—Action of blowout coil upon an arc between contacts.

when placed in a magnetic field is determined by the polarity of the field and the direction of the current. The same rule applies to an electric arc in a magnetic field. So, by having the magnetic field of the blowout coil of the correct polarity, the arc can be forced to the tips of the contact and stretched out until it is broken.

The blowout coil winding carries the same current as the contactor. So the stronger the arc, the stronger the flux field to blow it out.

The diagrams in figure 89 show the action of the magnetic field upon the arc. Also, you can see in this diagram how the main contacts are opened.

Most magnetic blowout coils have the inner surface of the magnet poles lined with asbestos. This prevents the arc from jumping to the pole faces.

In other types of magnetic blowout coils, the arc is blown into an insulated channel called an ARC CHUTE. Larger contactors have the arc extinguished by oil. Regardless of how it is done, the main thing is to see that the electric arc is extinguished before it has time to burn the contacts.

DRUM CONTROLLERS

Figure 90 shows the wiring diagram for a drum controller used to start and reverse a shunt motor. This controller has two sets of movable contacts, 1 to 5 and *V* to *Z*, and two sets of stationary contacts, *E* to *J* and *A* to *C*.

As previously explained, the movable contacts are copper segments mounted upon the drum. In this case, the two sets are mounted on opposite sides of the drum. A top view of the drum, shown in the small figure in the lower left corner, should help you to see how this is done. The stationary contacts are also on opposite sides of the drum as shown on the inserted figure. They are not fastened to the drum but can make contact with the segments on the drum.

In diagram 90, the movable contacts are laid out flat to make it easier for you to trace the circuits. Also the starting resistance is shown connected between the stationary contacts *G* to *J*. Actually these resistors would be in the form of grids which would be connected between the contacts *G* to *J*.

Look at the small sketch in the lower left corner, and imagine rotating the drum in a clockwise direction. The movable segments 1 to 5 would approach the stationary contacts *E* to *J* on one side of the drum. On the other side of the drum, movable segments *V* to *Z* would approach stationary contacts *A* to *C*.

Now take a look at the flat diagram. Suppose you rotate the drum to your left. Both sets of movable segments will be moved toward the left of the flat diagram indicated by the dotted drawings. The first step of this movement will bring movable seg-

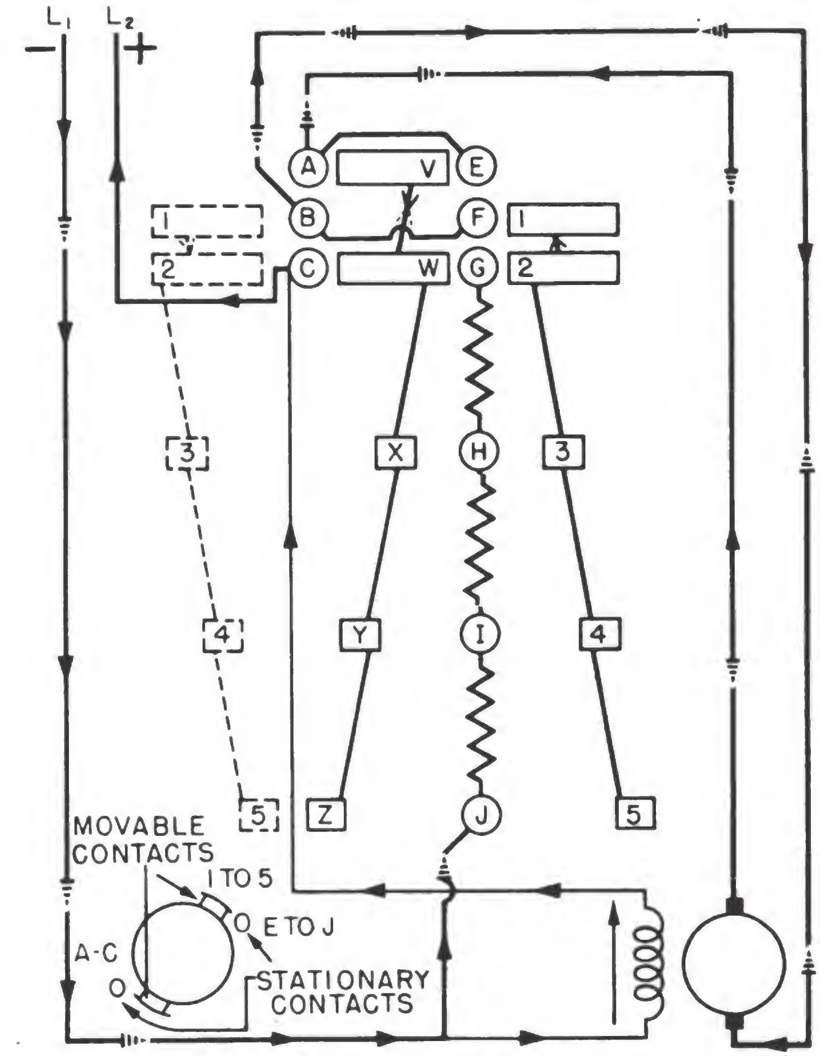


Figure 90.—Diagram of a starting and reversing drum controller.

ments 1 and 2 into contact with stationary contacts *F* and *G*. And movable segments *V* and *W* will contact stationary contacts *A* and *C*.

Now trace a circuit, shown by the heavy arrows, from L_1 to stationary contact *J*, through the resistance and contacts *I* and *H* to *G*, through the movable segment 2, through the jumper to movable segment 1, to stationary contact *F*, through the jumper to stationary contact *B*, from stationary contact *B* through the armature to stationary contact *A*, to movable segment *V*, through the jumper to movable segment *W*, to stationary contact *C*, and to L_2. Now, trace that circuit again.

Move the segment another step in the same direction. This brings movable segment 3 into contact with stationary contact *H*. Thus a part of the starting resistance is shorted out. The

current will flow from stationary contact *H* to movable segment 3 and through the jumper to movable contact 2, and continue through the same circuit as it did before. Successive movements of the controller in the same direction will bring movable segments 4 and 5 into contact with stationary contacts *I* and *J*, respectively, thereby shorting out the starting resistance step by step.

This is as far as the controller can be moved in this direction. The circuit is from L_1 to *J*, to movable segment 5, through the jumpers to movable segment 1, to stationary contacts *F* and *B*, through the armature to stationary contact *A*, to movable segment *V*, through the jumper to movable segment *W*, to stationary contact *C* and to L_2.

You will notice that movable segments 1, 2, *V*, and *W* are long enough to continue to touch the stationary contacts as the drum is rotated. This permits the shorter segments to touch the stationary contacts.

Now trace the circuit (small arrows) through the shunt field. Notice the direction of the current.

To reverse the motor, move the controller to the right. This brings the movable segments 1 to 5 around to the opposite side as shown by the dotted segments 1 to 5. At the same time movable segments *V* to *Z* are moved toward stationary contacts *E* to *J*. When the controller is moved into the first position in this direction, the movable segments 1 and 2 contact stationary contact *B* and *C*. And movable segments *V* and *W* contact stationary contacts *E* and *G* respectively.

Before you try to trace any circuits, be sure you have well in mind these new positions of the movable elements. Another reference to the small sketch in the lower left corner of the figure should help you to see how the movable segments are brought into the new positions.

With movable segments *V* and *W* in contact with stationary contacts *E* and *G*, and movable segments 1 and 2 in contact with stationary contacts *B* and *C*, you can trace a circuit as shown by the arrows, with dotted heads.

This circuit is from *L* to stationary contact *J*, through the resistance to stationary contact *G*, to movable segment *W*, through the jumper to movable segment *V*, to stationary con-

tact A, through the armature to stationary contact B, to movable contact 1, through the jumper to movable segment 2, to stationary contact C, and back to L_2.

As the controller is advanced step by step in this direction, the resistance is cut out step by step by movable segments X, Y, and Z.

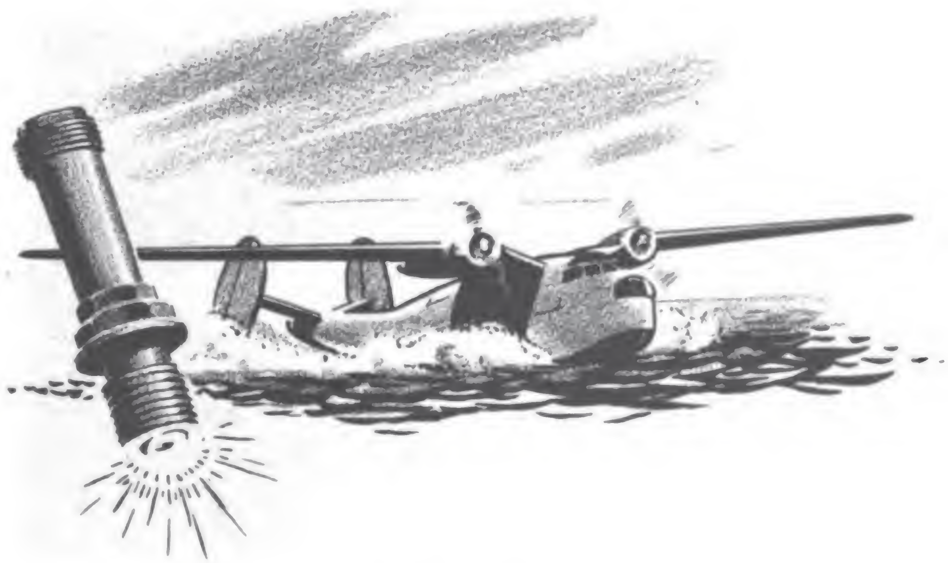
Again check the direction of the current through the shunt field. It hasn't changed. But the direction of the current through the armature has changed. Therefore, the direction of rotation of the motor is reversed.

Study the diagram in figure 90 until you are sure you understand how this drum controller works. Then take a diagram of one of the drum controllers used on board your ship. Study until you can trace the circuits just as you did in diagram 90. Find another drum controller used for a different purpose and do the same thing. By then you should be convinced there is nothing mysterious about drum controllers. They just provide a method by which an operator can make and break circuits.

Both the movable segments and the stationary contacts are fitted with removable copper shoes. These copper contacts should be kept in good condition and replaced when they become pitted or burned to the extent that they do not make contact over their entire surface.

The contacts are separated from each other by heavy fireproof insulation. This prevents arcs jumping from one contact to another. Always be careful to see that this insulation is back in place after the controller has been opened for any reason.

The contacts are provided with magnetic blowout coils to extinguish the electric arcs which are drawn when the circuits are broken. And in heavy duty controllers, each contact has its own blowout coil. In addition, overload protection and low voltage protection are provided.



CHAPTER 10

MAGNETIC CONTACTORS

SOME WORK AUTOMATICALLY

The controller shown in figure 91 is of the MAGNETIC CONTACTOR type. You will notice there is a magnetic contactor for each line. These contactors are controlled by a starting button. There are two auxiliary contacts to keep these line contactors closed afer the start button is released. There are line fuses and an overload relay for protection.

A manual control for the field rheostats is used to control the speed of the motor. And in addition, there are two SERIES LOCK-OUT CONTACTORS, which are ordinarily called ACCELERATING CONTACTORS.

Don't let the name ACCELERATING CONTACTORS scare you. In simple language, they are the contactors which automatically cut out the starting resistance as the motor comes up to speed.

The operator presses the start button and the controller does the rest of the work. It closes the main line contactors and cuts out the starting resistance at just the right time. This controller would, in general, be classified as semi-automatic, but as a particular type of controller, it is called an AUTOMATIC STARTER.

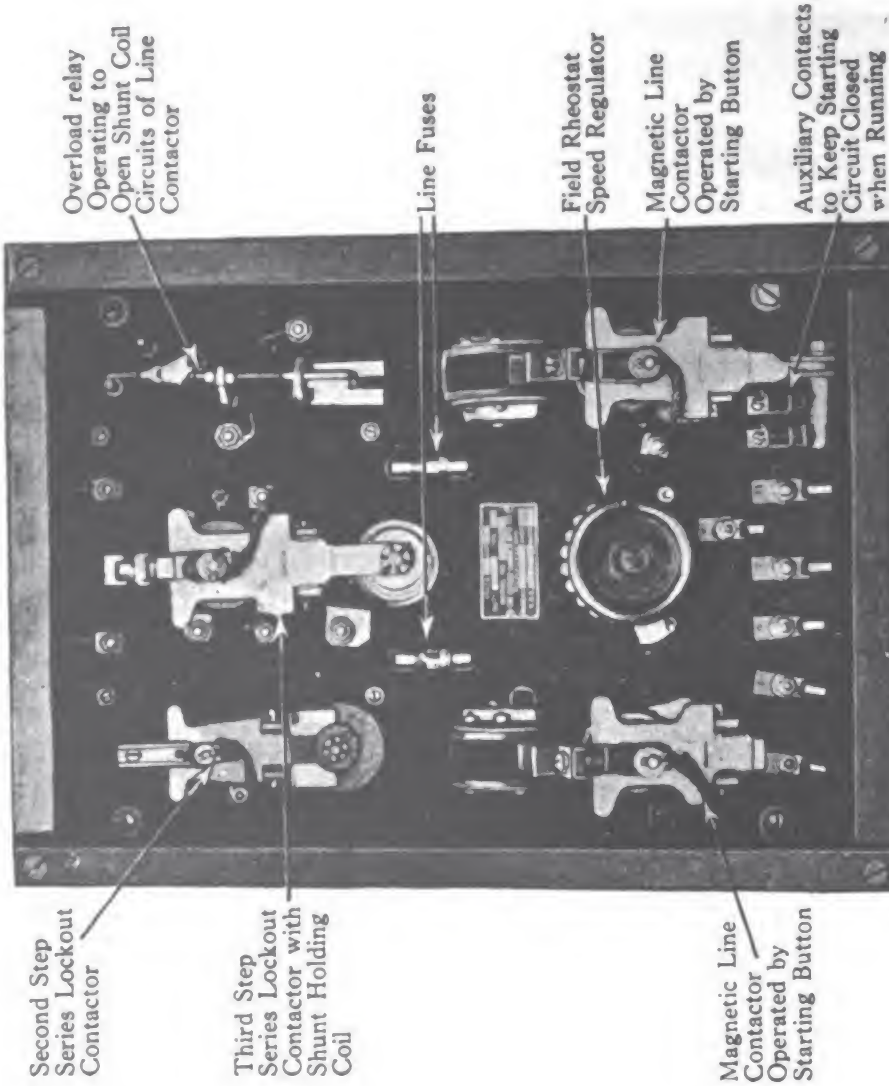


Figure 91.—Automatic starter with speed regulator.

HOW THEY WORK

Before studying the circuits and operating principles of a controller of this type, you should know how the magnetic contactors operate. A magnetic contactor is simply a switch operated by a solenoid. The contactor is generally closed by energizing the solenoid and is opened by its own weight or a spring when the solenoid is de-energized.

Don't confuse the magnetic contactor with a MAGNETIC RELAY. The magnetic contactor is the switch in the circuit being controlled, while the magnetic relay is a device which controls a circuit according to the changes of current in another circuit. Operation of relays and their use with magnetic contactors, will be explained later in this chapter.

In general, there are two types of magnetic contactors. The SHUNT CONTACTOR, as the name implies, is connected across the line. Its solenoid coil is wound with many turns of fine wire. The SERIES CONTACTOR has its solenoid coil connected in the line. The coil is wound with a few turns of heavy wire and carries the full-load current of the motor being controlled.

SHUNT CONTACTOR

Figure 92 shows how a shunt contactor is connected into the circuit. The shunt coil of the solenoid is connected in the PILOT

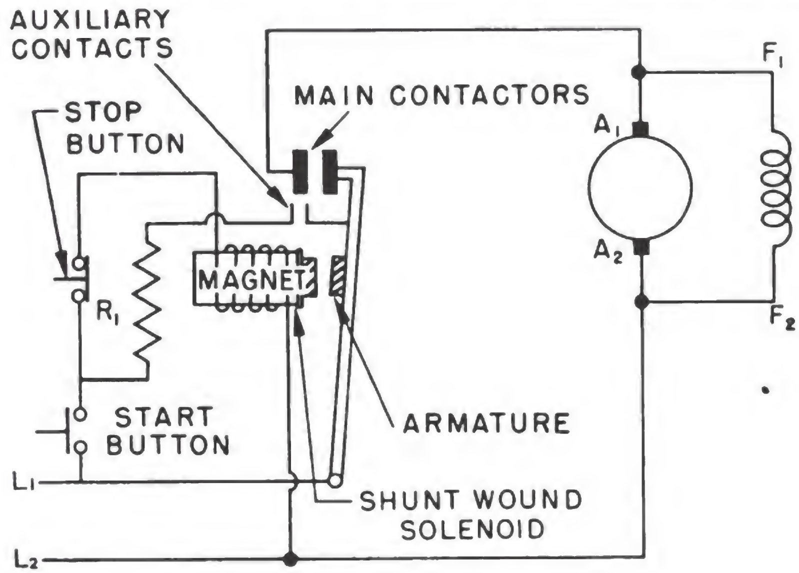


Figure 92.—A shunt contactor.

CIRCUIT, that is, the circuit which is controlled by the start and stop buttons. This pilot circuit is across the line, and therefore the shunt coil is across the line.

The stop button is normally closed, and the start button is normally open. So, to complete the pilot circuit it is necessary for the operator to close the start button. When the start button is closed, a circuit can be traced from L_1 through the start and stop buttons, through the shunt coil, and to L_2—and this energizes the solenoid.

When the solenoid is energized, it attracts the soft iron armature secured to the arm of the main contactor. The main contactors are closed, and a circuit is completed from L, through the motor to L

But what happens when the start button is released? Releasing the start button breaks the circuit from L, through the start and stop buttons, and through the solenoid coil to L_2. You know that if the solenoid is de-energized, the contactor arm will be released. So some means must be provided to keep the solenoid energized after the start button is released. The AUXILIARY CONTACTS do the job. When the main contactors are closed, the auxiliary contacts are closed. You will notice that one of the auxiliary contacts is connected to the main contactor arm, which in turn is connected to L_1. So when the auxiliary contacts are closed, a circuit is completed from L_1 through the auxiliary contacts, through the resistance R_1, and through the shunt coil of the solenoid to L_2. Now the shunt coil circuit is complete, and the solenoid holds the contactor arm in a closed position.

To de-energize the solenoid and open the main contactors, PRESS the stop button. This breaks the solenoid circuit. The main contactors are then opened, along with the auxiliary contacts. The solenoid remains de-energized until the start button is pressed again.

You know that it takes a stronger solenoid to close the main contactor than to keep it closed. At the time the start button is pressed, there is no resistance in the shunt coil circuit. Enough current flows in the circuit to give the solenoid the number of ampere-turns required to close the contactor. Once the contactor is closed, the ampere-turns may be reduced, because less magnetic attraction is required to keep the contactor closed. So, the current through the shunt coil may be reduced by putting the resistance R_1 in the circuit and thus protecting the coil from damage.

Here is a point to remember in case the contactor arm should have a tendency to remain closed after the stop button has been pressed. The iron armature on the contactor arm and the iron core of the solenoid may retain some residual magnetism. A contactor which is designed to open by its own weight might be held closed by this residual magnetism. To prevent this, the iron armature of the contactor arm is separated from the iron core of the solenoid by a small air gap or some non-magnetic material such as a strip of brass.

The shunt contactor is particularly suitable for remote control systems. Since the shunt coil is wound with fine wire and

carries a small current, the master start-stop switch may be located a considerable distance away. The conductor connecting the master switch may be of the smallest wire in general use aboard ship. It is also possible to control the shunt contactor from several different places by putting more master start-stop switches in the pilot circuit.

Contactor panels may be arranged in so many different ways that it would be impractical to try to cover all of them in this book. But the operation of all these panels depends upon a few elementary principles. You should be thoroughly familiar with these principles, and the contactor panels explained in this chapter are presented for that purpose. Study them until you understand the operating principles employed in each one.

ACROSS-LINE STARTER

Figure 93 shows a wiring diagram for an ACROSS-LINE CONTACTOR PANEL more commonly known as an ACROSS-LINE

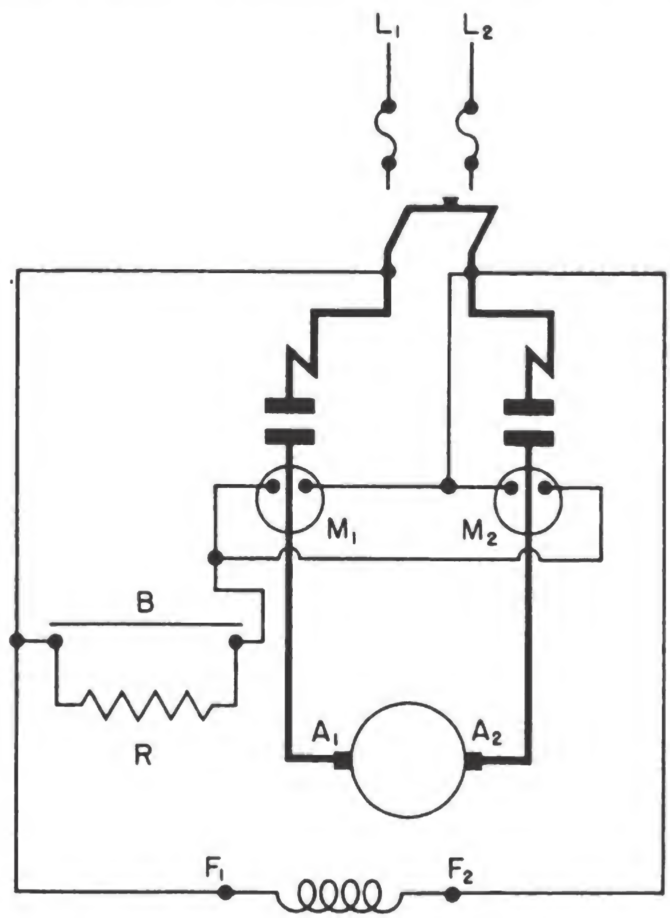


Figure 93.—Across-line starter panel circuit.

STARTER. This type of STARTER can be used with small motors, which require no starting assistance.

This panel is connected to the line by a fused double-pole, single-throw, knife switch. When the knife switch is closed, the shunt coils of the solenoid of main line contactors M_1 and M_2 are energized. This causes the solenoid to operate and to close the main line contactors. When the main line contactors are closed the motor is connected directly across the line.

The shunt coils are continuously energized while the knife switch is closed and the motor is running. The coils will gradually heat up. And unless some provision is made to cut down the heating effect, the insulation on the coils will deteriorate. The heating is prevented by placing a resistance in the shunt coil circuit after the contactors have been closed. You can see how this is done by referring to figure 93.

When the main line contactors are open, the resistance R is shunted out of the shunt coil circuit by the bridge B. This bridge is mechanically connected to the arm of main contactor M_1. When the main contactor M_1 closes, the bridge B is lifted from the contacts of the resistance R. The resistance R is no longer shunted but is in the shunt coil circuit. This added resistance in the shunt coil circuit reduces the current to a value which is sufficient to keep the main contactors closed, but will not cause the coils to overheat.

This type of starter can be used only on small motors that may be connected directly across the line. It doesn't provide a method for speed control, and it isn't automatic. The only safety feature is the protection given by the line fuses.

An across-line starter that can be connected for remote control operation is shown in figure 94. Only one main line contactor is shown in this starter. However, the same principle can be applied to any number of contactors.

On this panel, when the line switch is closed, the shunt contactor coil is not energized. It is energized by the pilot circuit and the start-stop push buttons.

When the start button is pressed, the shunt coil of the main contactor is energized and the main contactor closes. At the same time the auxiliary contacts at H are closed. This completes

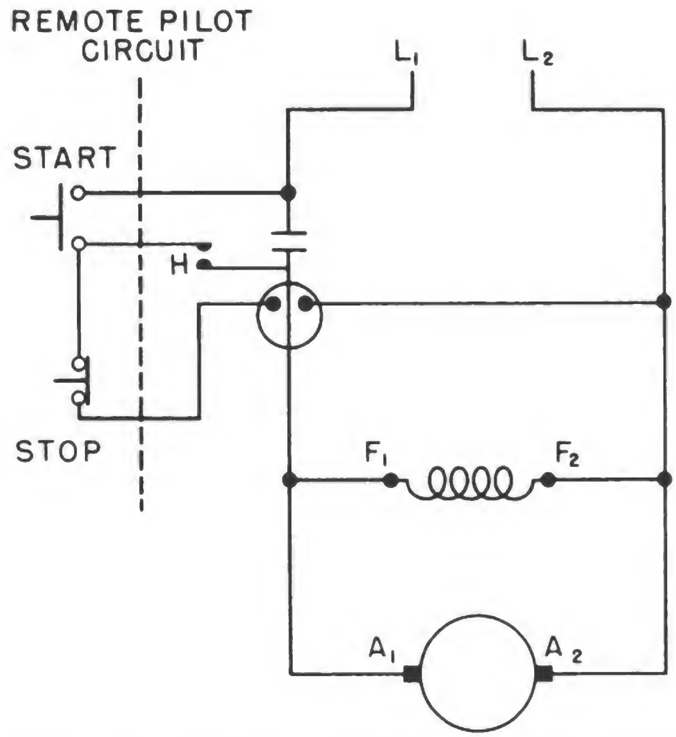


Figure 94.—Across-line starter with remote control.

a circuit through the stop button and the shunt coil. The start button then may be released.

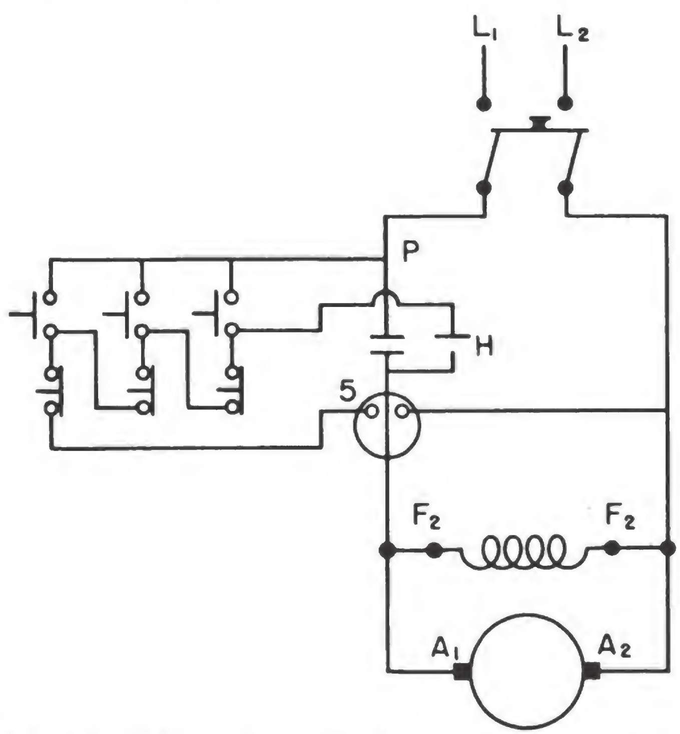


Figure 95.—Across-line starter with three remote control start-stop switches indicated.

To stop the motor, simply press the stop button. This breaks the circuit through the shunt coil and the main contactor opens.

Figure 95 shows how this starter may be controlled from several points. As many start-stop buttons as desired may be used. The main thing you should notice in this diagram is how the buttons are connected. The start buttons are connected in PARALLEL, and the stop buttons are connected in SERIES. Remember that when connecting more than one start-stop button in a control circuit—connect the start buttons in parallel and the stop button in series.

FLOAT SWITCH

Figure 96 shows how a starter of this type can be operated automatically by a float switch, which takes the place of the

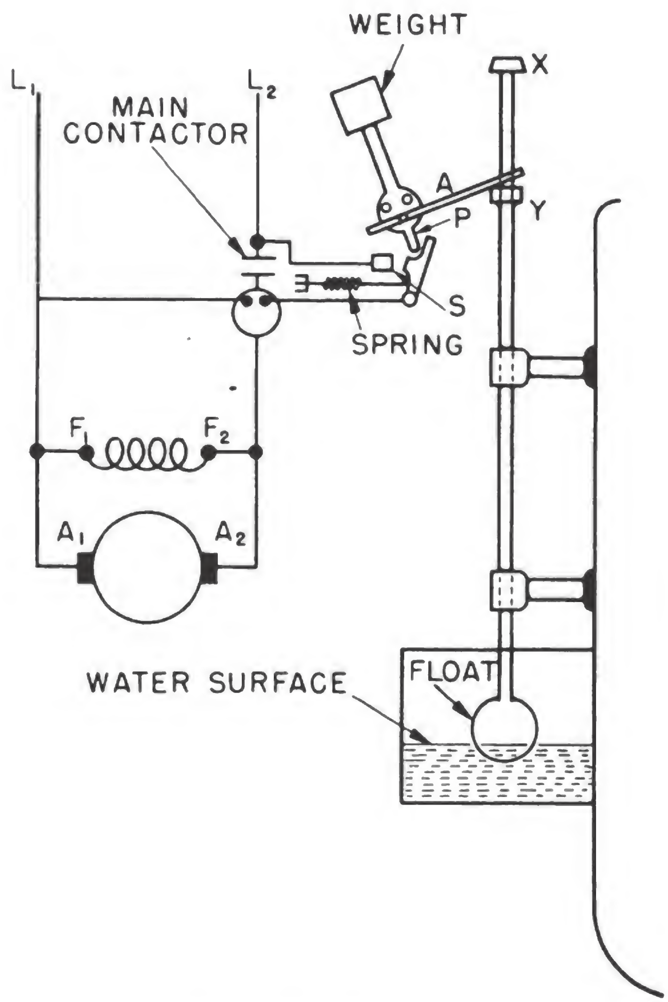


Figure 96.—Float switch.

start-stop button. Also notice there are two control wires in the pilot circuit instead of three as in the previous examples.

When the water raises the float above a certain level, knob *Y* raises arm *A*. Arm *A* swings the weight to the left. Projection *P* opens the auxiliary switch *S*. This de-energizes the shunt coil and the main contactor opens, stopping the motor.

When the water goes down to a certain level, knob *X* forces arm *A* downward. This swings the weight to the right and the spring closes auxiliary switch *S*. The shunt coil of the contactor is energized and the contactor closes. The motor starts and runs until the water reaches a level which will cause the float to again open the shunt coil circuit and stop the motor.

By adjusting the knobs *X* and *Y*, the water can be kept within the desired level limits.

Similarly a pressure switch, a scale switch, a limit switch, a thermostat, a thermocouple, or a photo cell could be placed in the pilot circuit to control the magnetic contactor.

Now for the difference between the three-wire control circuit and the two-wire control circuit.

If the magnetic contactor has a three-wire control circuit as shown in figure 94, it automatically opens upon voltage failure. And it will remain open after the voltage is restored, until the start button is pressed. This is known as LOW VOLTAGE PROTECTION. Such protection is essential on all machines that can cause damage by starting unexpectedly.

If the magnetic contactor has two-wire control as shown in figure 96, the motor will start automatically when voltage is restored after a failure. This type of protection is called LOW VOLTAGE RELEASE PROTECTION.

CHAPTER 11

OVERLOAD PROTECTION

OVERLOAD RELAY

OVERLOAD PROTECTION may be obtained by a fuse, or by magnetic or thermal overload relays.

Figure 97*A* shows how a MAGNETIC OVERLOAD RELAY may be connected in the control circuit. When an overload of current causes the relay to operate, it de-energizes the shunt coil of the control circuit. The contactor opens and the power is cut off. The relay then drops back into its normal position and the control circuit is again complete. However, the main contactor doesn't operate because the auxiliary contacts also opened when the main contactor opened. So the motor doesn't start again until the start button is pressed. In the meantime, the cause of the overload can be removed.

One type of overload relay, figure 97*B*, consists of a solenoid with a movable iron core which serves as a plunger. The solenoid is wound with a few turns of heavy wire and is connected in series with a load.

The solenoid is set to lift the plunger when the current through the coils exceeds a predetermined value. When the plunger is

lifted above its normal position, it opens the relay contacts. This relay has an instantaneous trip, and must be set so that it will not be opened by a high starting current, but will trip only when the load current becomes abnormally high.

By adding a DASH POT to the relay core, it can be made into a TIME DELAY OVERLOAD RELAY. This prevents the relay from

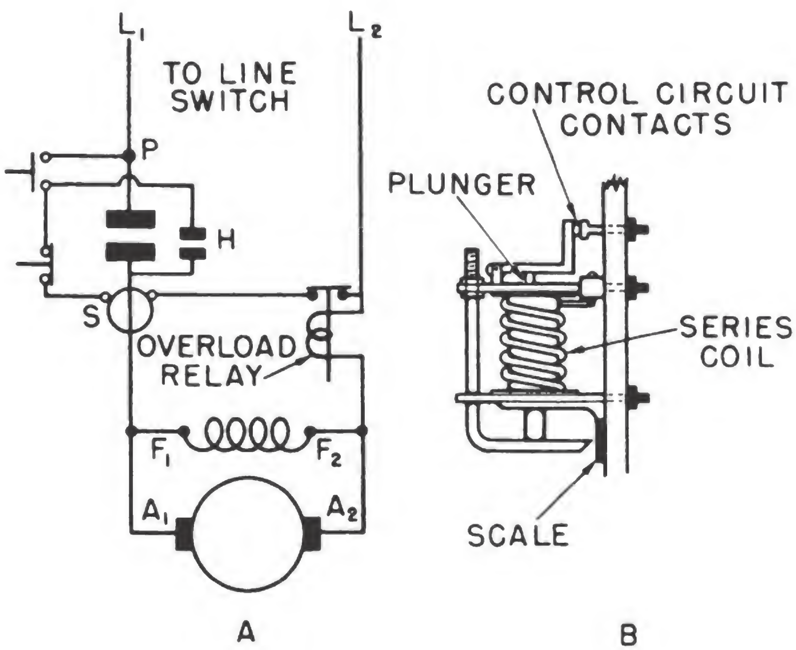


Figure 97.—Overload relay.

tripping when a momentary increase in current is present such as at starting. But if the overload continues, the relay will trip after a brief period.

OVERLOAD RELAY USED WITH TWO-WIRE CONTROL SYSTEMS

The overload relay just described works O.K. in a three-wire control. But to make it work in a two-wire control, it is necessary to add another winding on the solenoid.

Figure 98 shows an overload relay connected to operate in a panel that does not have three-wire control. You will notice that in addition to the heavy series overload coil *OL*, the solenoid has another coil *C*, called a holding coil. It has many turns of

fine wire and is connected directly ACROSS THE LINE. Thus, it is energized when the line switch is closed and remains energized until the line switch is opened.

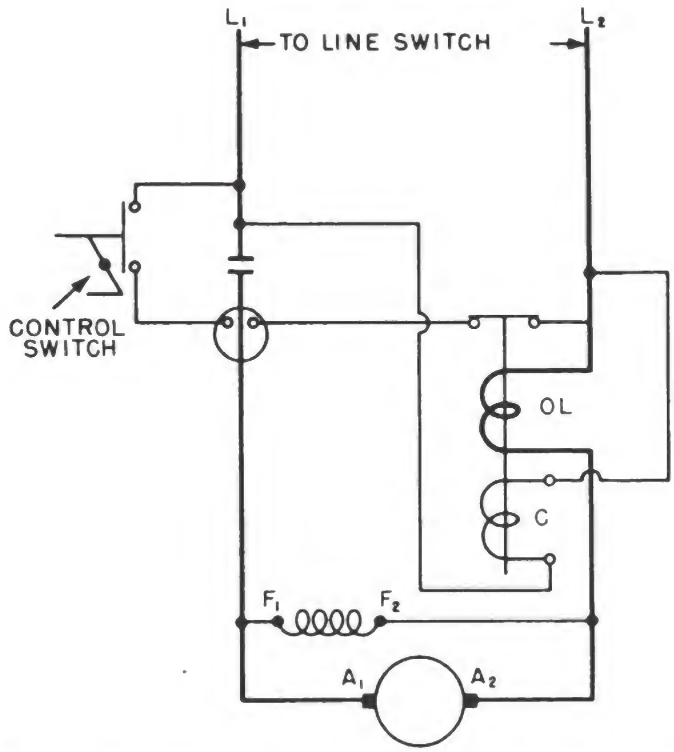


Figure 98.—Overload relay with shunt holding coil.

The magnetic pull of the holding coil *C* is in the same direction as the overload coil *OL*. The holding coil alone is not strong enough to lift the relay plunger, but it is strong enough to hold the plunger up once it has been raised.

When the load current exceeds a predetermined value, the overload coil raises the plunger. The shunt coil circuit opens and the main contactors open. The motor stops. But when the main contactors open, the overload coil *OL* is de-energized. If there were no HOLDING COIL, the plunger would drop, completing the circuit through the shunt coil. The contactors would close again and current would flow through the overload coil. If the overload still existed, the relay would open the shunt coil circuit again. You can see how this would result in a continual clattering of the overload relay and main contactor. But with the holding coil on the relay, the relay keeps the control circuit open until the operator can open the line switch and remove the cause of the overload. Then the panel is ready to operate again.

MAGNETIC CONTACTOR PANEL WITH STARTING RESISTANCE

Figure 99 shows how magnetic contactors can be used to cut out starting resistance. Four positions are shown for the STARTING ARM. Close the line switch when the starting arm is in OFF position.

Moving the starting arm to the first position makes it contact segment 1. The shunt field is now connected directly across the line. Trace the circuit from L_1 through the starter arm, segment 1, terminal F_1, the shunt field, and terminal F_2, to L_2. Notice that this circuit will be the same regardless of the next two positions of the starting arm.

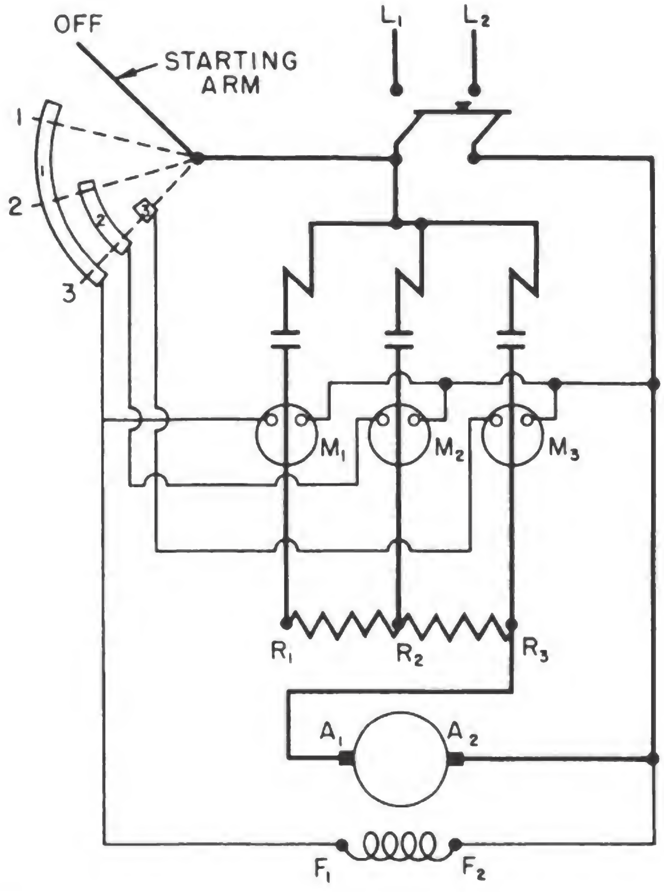


Figure 99.—Magnetic contactor circuit with starting resistance.

Also trace a circuit from L_1 through the starter arm, segment 1, and the shunt coil of contactor M_1, to L_2. Thus the shunt coil is energized and contactor M_1 is closed. This completes a circuit

from L_1 through contactor M_1 and starting resistance R_1 to R_3, and through the armature to L_2. Both the field and armature are excited, so the motor starts.

The starter arm is then moved to the second position, where it makes contact with segment 2. A circuit is completed through the shunt coil of the contactor M_2. Contactor M_2 is closed, and a circuit is completed from L_1 through resistance R_2 to R_3, and through the armature to L_2. The resistance R_1 to R_2 has been shunted out.

Finally the starting arm is moved to the third position, where it makes contact with segment 3. This completes a circuit through the shunt coil of contactor M_3. Contactor M_3 is closed, and a circuit is completed from L_1 through contactor M_3, to the armature, and to L_2. The entire starting resistance has been shunted out.

If the starting resistance is heavy enough to carry the load current continuously without overheating, this panel could also be used to obtain speed control below normal. The resistance could be cut in and out of the armature circuit by shifting the starter arm. Positions 1, 2, and 3 would give three speeds—the normal speed in position 3 and lower speeds in positions 2 and 1.

You will notice that the shunt coils of all three contactors are across the line at full speed. To reduce the heating effect, a resistance such as the one shown in figure 93 would be provided. It has been omitted here to simplify the wiring diagram.

A panel of this type can be used on a moderately sized motor and where automatic control isn't desired.

CUTTING OUT STARTING RESISTANCE AUTOMATICALLY

In figure 100 you can see how magnetic contactors are used to cut out starting resistance automatically. You will notice that in addition to main contactor *M* there are three accelerating contactors 1*R*, 2*R*, and 3*R*. Be sure you see the two series relays *C* and *B*, and the two mechanically operated bridges *E* and *F*.

The series relays *C* and *B* are normally kept closed by their own weight. But if current exceeding the predetermined value flows through the series coil of relay *C*, the plunger is lifted and

the circuit is opened at point X. When the current goes below this predetermined value, the plunger drops and closes the circuit at X. Relay B operates in the same manner. However, the series coil operates the plunger B on a LOWER VALUE of current than is required by relay C.

The bridges E and F are connected mechanically to the arms of contactors $1R$ and $2R$, respectively. When contactor $1R$ is

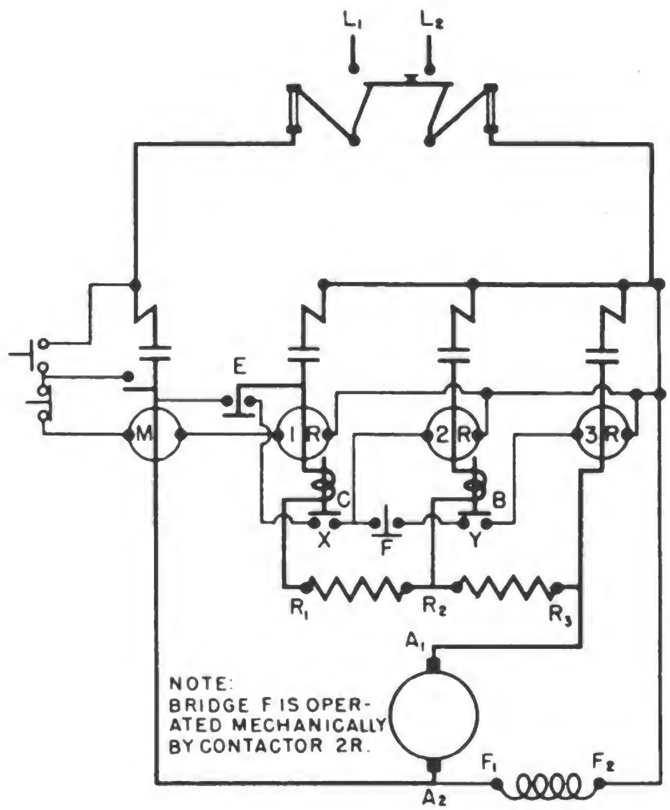


Figure 100.—Contactor panel for reducing starting resistance automatically.

closed, the bridge E closes the circuit at that point. Similarly, when contactor $2R$ closes, bridge F closes the control circuit at that point.

Now suppose you put the panel to work, and let it cut out the starting resistance as the motor comes up to speed.

HOW IT WORKS

CLOSE the LINE SWITCH and PRESS the START button. A circuit is completed from L_1 through the start button and stop button to shunt coils M and $1R$ to L_2. Notice that the current can't go

through shunt coils $2R$ and $3R$, because bridges E and F are open. Contactors M and $1R$ are closed. This completes a circuit from L_1 through contactor M, through the armature, through the resistance R_1 to R_3, through the series relay coil C, and through contactor $1R$ to L_2. Also notice that the circuit through the shunt field is completed. The motor starts.

When accelerating contactor $1R$ closed, the bridge E also closed. This would appear to complete the circuit through the shunt coil of $1R$, but something else happens which prevents this. At starting, the motor draws a high current. This current flows through the series coil of relay C. The high current causes the relay to operate and the circuit to the shunt coil of contactor $2R$ is opened at point X.

However, as the motor speed increases and the counter emf builds up, the current is reduced. When the current is reduced to the correct value, the series relay drops back to its normal position and closes the circuit at point X.

There is now a circuit through shunt coil $2R$. Contactor $2R$ closes, and a new circuit may be traced from L_1 through contactor M, the armature, resistance R_2 to R_3, and contactor $2R$ to L_2. The resistance from R_1 to R_2 has been shunted.

The mechanically operated bridge F is closed when contactor $2R$ is closed, but the control circuit through shunt coil $3R$ isn't closed. It isn't closed because series relay B opens the circuit at Y.

Remember—when contactor $2R$ closed, part of the armature resistance was shunted out. Therefore, the speed of the motor increases and the counter emf goes up, further reducing the armature current. This reduction in current permits the plunger of series relay B to drop to its normal position, completing the circuit through shunt coil $3R$ and closing contactor $3R$. When contactor $3R$ closes, the entire starting resistance is shunted and the motor has reached its normal operating speed.

To use this type panel, it will be necessary for you to provide some method to prevent the shunt coils of the contactors from overheating. You can do this by putting a resistance in series with them after all the contractors have been closed.

Another method would be to place a resistance in series with the main line contactor coils and cut out the shunt coils of the other contactors when the motor reaches full speed. The first

method has been explained. The other method will be explained later in this chapter.

DISCONNECTING ACCELERATING CONTACTORS AT FULL SPEED

Figure 101 is a diagram of a shunt contactor panel in which two of the accelerating contactors drop out of the line when the motor comes up to full speed. Also, it shows how a resistance is placed in series with each of the shunt coils of the other contactors when the contactors are closed.

Notice the bridges C, D, E, and F. They are connected mechanically to the arms of contactors M, $1R$, $2R$, and $3R$ respectively. You will also notice that the bridge C is NORMALLY OPEN, but closes when contactor M closes. Bridge D normally rests on the lower set of contacts, but is across the upper contacts when contactor $1R$ is closed. Bridge E works similarly with contactor $2R$. Bridge F normally shorts together three contacts, but when contactor $3R$ closes, the bridge is lifted and the circuits through the three contacts are opened.

Series relays L, M, and N are operated by the current through contactors M, $1R$, and $2R$, respectively. These relays are closed when the circuits through the contactors are de-energized. Each relay is opened when the current through its series coil exceeds a predetermined value. The relay closes again when the current drops below a certain value.

Notice that relays L, M, and N open and close the control circuits through shunt coils $1R$, $2R$, and $3R$, but they are caused to operate by the armature current through contactors M, $1R$, and $2R$.

Now suppose you close the line switch, press the start button, and see how this panel operates.

HOW IT WORKS

When the line switch is closed and the start button is pressed, a circuit is completed through shunt coil M, through bridges D, E, and F to L_2. Contactor M is closed, and a circuit is completed

from L_1 through M, through the starting resistances R_1, R_2, and R_3, and through the armature to L_2.

When contactor M closes, bridge C is lifted to complete a circuit through the shunt field. It also appears that a circuit through the shunt coil 1R would be completed. But the high starting current through the series coil of relay L causes the relay to operate and the circuit through shunt coil 1R to be kept open. However, as the motor picks up speed, the starting current is reduced. When the current is reduced to the correct value, relay L drops back into a closed position. The circuit through shunt coil 1R is completed, and the contactor closes.

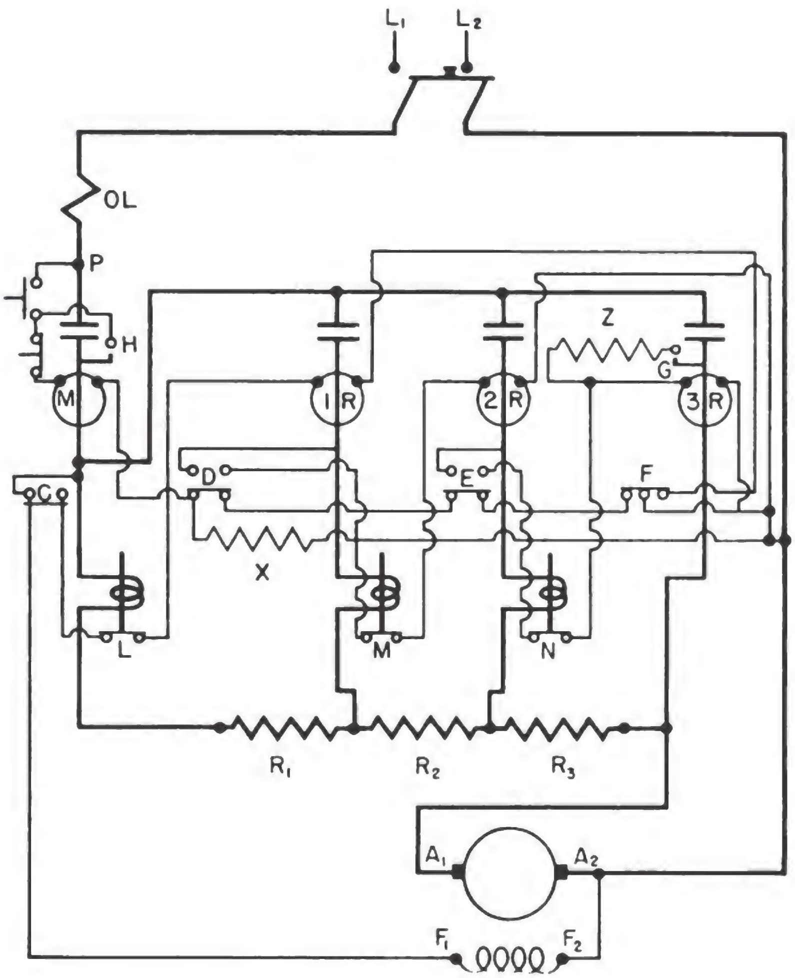


Figure 101.—Shunt contactor panel with two automatic disconnecting accelerator contactors.

When contactor 1R closes, resistance R_1 is shunted out of the armature circuit. The motor speed increases and the starting current decreases still further.

When contactor $1R$ closes, bridge D is lifted. This does two things. It breaks the original circuit through shunt coil M and places the resistance X in the circuit. Resistance X prevents the shunt coil M from overheating. The bridge is also lifted into contact with the upper set of contacts and completes a circuit through shunt coil $2R$. That is, the circuit is complete when relay M closes. Relay M was opened by the armature current through its series coil, and it closes when the armature current is reduced to the correct value. Thus a circuit through shunt coil $2R$ is completed and contactor $2R$ closes. Starting resistance R_2 is now shunted out of the armature circuit.

When contactor $2R$ closes, bridge E and relay N operate to complete the circuit through shunt coil $3R$, just as bridge D and relay M completed the circuit through shunt coil $2R$.

Contactor $3R$ is closed and the entire starting resistance is shunted out. When contactor $3R$ closes, bridge F is lifted from the three contacts in the control circuit. This opens the circuit through shunt coil $1R$, and contactor $1R$ opens. When contactor $1R$ opens, bridge D drops. The circuit through shunt coil $2R$ is opened, and contactor $2R$ opens. Bridge E drops. The original circuit through shunt coil $3R$ is opened, but the shunt coil isn't de-energized. When the contactor $3R$ closes, the auxiliary contacts at G complete a circuit through resistance Z and shunt coil $3R$. This keeps $3R$ closed.

So you have two contactors, $1R$ and $2R$, out of the circuit. Furthermore, the shunt coil M is protected by resistance X, and shunt coil $3R$ is protected by resistance Z.

OL is an overload relay for protection against overloads.

SERIES CONTACTORS

On all the magnetic contactor panels discussed so far, the contactors are controlled by shunt coils. And the shunt coils are controlled by other devices placed in their circuits.

The operation of the series contactor is quite different from the operation of the shunt contactor. The operation of the series contactor depends upon the VALUE OF CURRENT FLOWING IN THE SERIES COIL. The series coil of the series contactor carries the line current; therefore the operation of the series contactor depends upon the amount of current flowing in the line.

The SERIES CONTACTOR IS HELD OPEN by a CURRENT when it EXCEEDS a PREDETERMINED VALUE, and CLOSES promptly when the current DROPS BELOW this value. Pin that down, and remember it!

The series contactor shown in figure 102 is a SINGLE COIL LOCKOUT CONTACTOR. Its operation depends upon the SATURATION OF A PORTION of the MAGNETIC CIRCUIT.

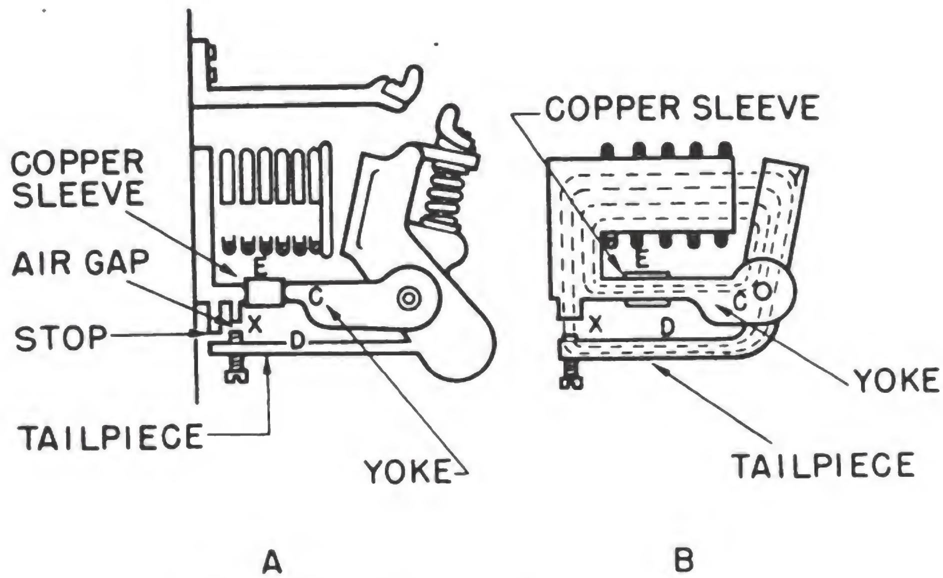


Figure 102.—Single coil lockout contactor.

You will notice there are two magnetic circuits—one through yoke *C*, and the other through tail piece *D*. The flux through *C* TENDS TO CLOSE the contactor, and the flux through *D* TENDS TO HOLD IT OPEN.

Take another look at the figure to make sure you understand how these two magnetic circuits affect the operation of the contactor. The flux through *C* tends to close it and the flux through *D* tends to hold it open.

Also notice that the cross section of yoke *C* is much smaller than the cross section of tail piece *D*. That means *C* will become saturated with flux much more easily than *D*. As long as the flux is below the saturation point of *C* most of the flux will go through *C* because the AIR GAP at *X* increases the reluctance of path *D*. However, when the CURRENT through the SERIES COIL GOES HIGH ENOUGH to cause the magnetic flux to SATURATE *C*, the flux will then go through *D*.

When the current through the series coil EXCEEDS a certain value, C becomes saturated and most of the flux goes through D. This holds the contactor OPEN.

When the current goes BELOW this value, C is no longer saturated. Almost all the flux will go through C, and the contactor is closed.

As the contactor closes, the air gap X is increased and still less flux goes through D. Thus the pull which tends to keep the contactor open is decreasing. Also, as the contactor closes, the distance between the armature Y and the tail piece is decreased, and the magnetic pull becomes greater. This causes the contactor to close rapidly and hold together with considerable force.

Ordinarily the contactor would close as the current is increasing, because C must become saturated before flux begins to build up in D. This difficulty is overcome by putting the copper sleeve E around C.

As the current increases, the flux field builds up. The flux field sweeping across the copper sleeve E INDUCES a VOLTAGE in the copper sleeve. The SLEEVE is a closed circuit with low resistance, and a large current flows. The induced current flowing in the copper sleeve SETS UP A MAGNETIC FIELD which OPPOSES the MAIN FLUX field and prevents it from passing through C. This CAUSES THE FLUX TO GO THROUGH D first and the contactor is held open.

The contactor may be set to operate on different values of current by adjusting the air gap at X. If the AIR GAP is INCREASED the contactor will close on a LOWER VALUE of current. If the AIR GAP is DECREASED the contactor closes on a HIGHER VALUE of current.

DOUBLE COIL LOCKOUT CONTACTOR

Another type of series contactor is shown in figure 103*A*. It is the DOUBLE COIL LOCKOUT CONTACTOR. BOTH COILS are connected in series with the armature of the motor. The upper coil D closes the contactor, and the lower coil C holds it open.

The iron surrounding coil D is worked NEAR the SATURATION POINT. Its magnetic pull is STRONG at LOW VALUES of current and INCREASES ONLY SLIGHTLY AS THE CURRENT INCREASES.

The iron around coil *C* is not saturated. Therefore the magnetic pull of this coil increases rapidly with any increases in current.

The graph shown in figure 103*B* shows how the magnetic pull of each coil varies with the current. As the current increases

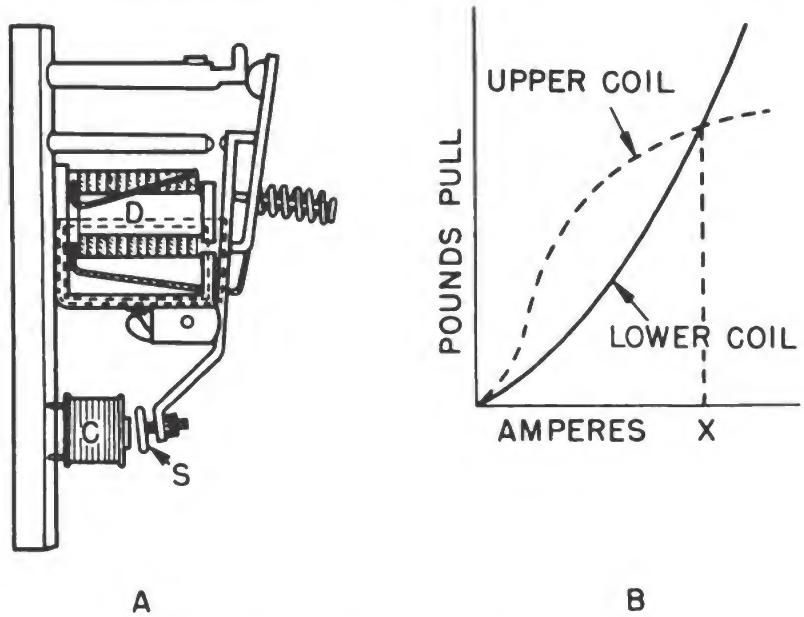


Figure 103.—Double coil series contactor.

from zero to point *X*, the magnetic pull of the coil *D* increases, as shown by the dotted line. The pull of coil *C* is shown by the solid line. When the current exceeds the value at *X*, the pull of coil *C* increases rapidly. But the iron around coil *D* has become saturated and its pull increases very slowly.

Thus when the current is high, coil *C* holds the contactor open. But when the current decreases below a certain value such as point *X*, the pull of coil *C* decreases more rapidly than the pull of coil *D*, and coil *D* closes the contactor.

The adjusting screw *S* is used to set the contactor for operation on different values of current.

SERIES CONTACTOR PANELS

Figure 104 shows the wiring diagram of a simple starter with SINGLE COIL LOCKOUT CONTACTORS. The main contactor *M* is of the shunt type and is controlled by the start-stop buttons. When

the start button is pressed, the main contactor M is closed. The shunt field is connected across the line and the starting resistances R_1 and R_2 are connected in series with the armature.

As soon as the counter emf reduces the armature current to the value at which contactor $1R$ is set to operate, $1R$ closes. This shunts out the resistance R_1 and inserts the series coil of contactor $2R$ in the armature circuit.

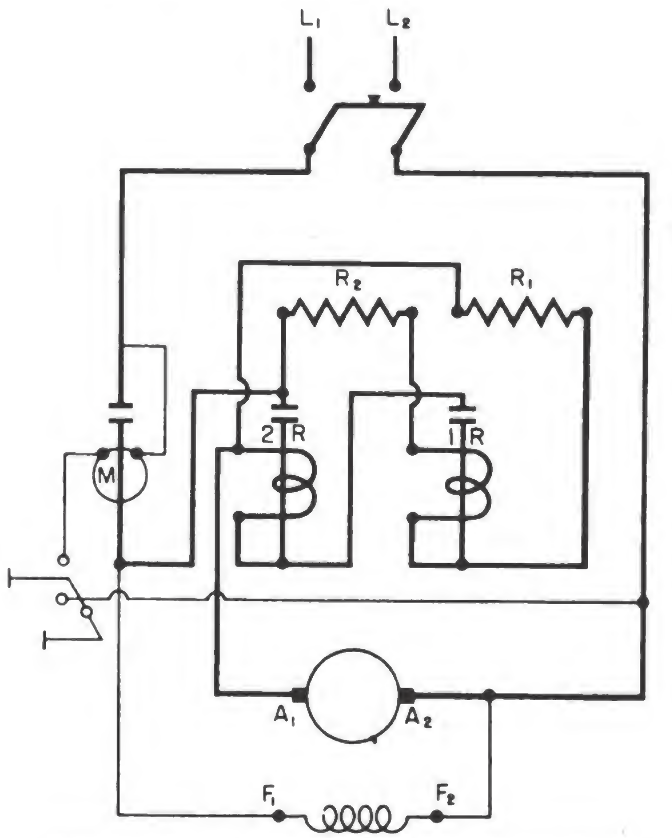


Figure 104.—Single coil lockout contactors.

The speed of the motor increases, because the resistance R_1 has been cut out. The counter emf also increases, and the armature current is reduced. When it is reduced to a value at which contactor $2R$ is set to operate, $2R$ closes and puts the armature directly across the line to operate at full speed.

DOUBLE COIL LOCKOUT CONTACTORS

Figure 105 shows a panel with double coil lockout contactors. You will notice that the main contactor M is again a shunt contactor and is controlled by a master switch.

When the start button is pressed, the shunt contactor M closes. This puts the shunt field across the line and all the starting resistance in series with the armature.

When the counter emf reduces the current to the correct value, contactor $1R$ closes. This shunts out resistance R_1 and the bottom coil D of the contactor. At the same time both coils E and F of contactor $2R$ are put into the armature circuit.

The speed of the motor increases because the resistance R_1 is cut out of the circuit. The counter emf goes up and the armature current is reduced. When the current is reduced to the value at which contactor $2R$ is set to operate, $2R$ will close. When contactor $2R$ closes, resistance R_2 is shunted out and the bottom coil F of contactor $2R$ is also shunted out. And the circuit is completed through both coils G and H of contactor $3R$.

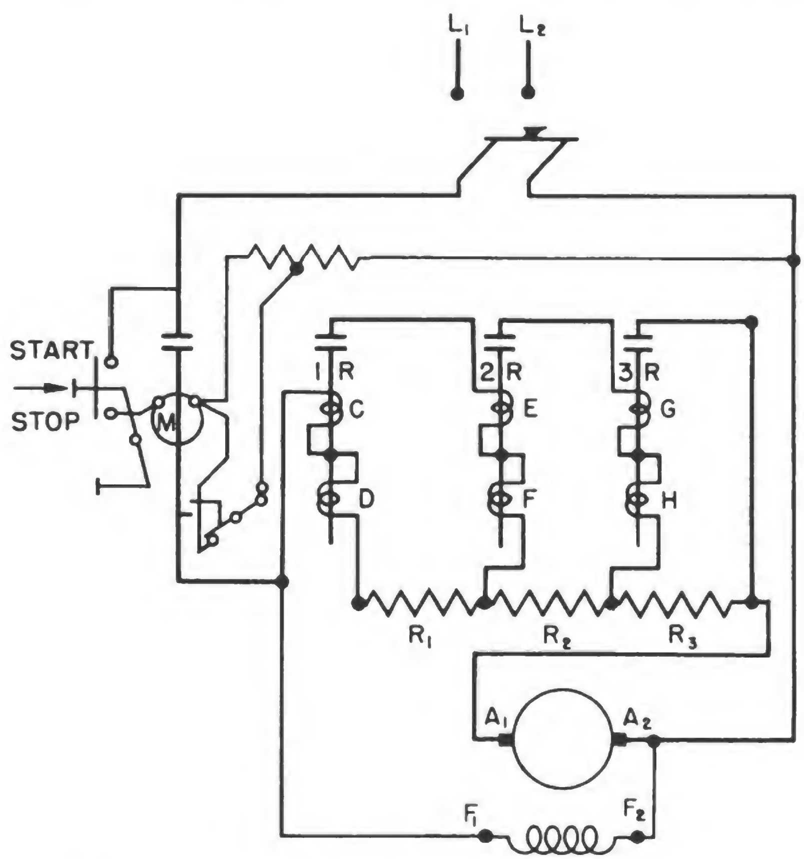


Figure 105.—Double coil series contactor panel.

When the armature current goes down to the correct value, contactor $3R$ closes and the armature is directly across the line. The entire starting resistance and the bottom coil H of contactor $3R$ have been shunted out.

Contactor panels employing series contactors are often referred to as CURRENT LIMIT STARTERS, because the operation of the accelerating contactors depends upon the value of the armature current.

Because of their simplicity, these panels require practically no interlocks and are not likely to cause trouble. However, some of them are not suitable for handling light loads, because the contactors will not remain closed.

CHAPTER 12

CIRCUIT BREAKERS

THEY PROTECT THE CIRCUITS

Figure 106 shows a special electric switch used to protect electrical circuits. It is called a CIRCUIT BREAKER—and break circuits is exactly what it does. It is generally designed to open the circuit when some abnormal condition, such as an overload, occurs.

The circuit breaker occupies more space than a fuse and its initial cost is higher. However, in many ways it is superior to the fuse. The circuit breaker can open the circuit more quickly and it can be reset easier after the cause of the overload has been removed. It may be adjusted to operate on different values of current and have a time element added to prevent opening of the circuit on a momentary overload that will do no harm. In addition to the overload protection feature, the circuit breaker may be made to give protection against voltage failure and reversed current. Furthermore, the circuit breaker may be opened and closed by remote control.

ONE TYPE OF CIRCUIT BREAKER

The circuit breaker shown in figure 106 has three sets of contacts—the MAIN CONTACT and TWO AUXILIARY contacts. That

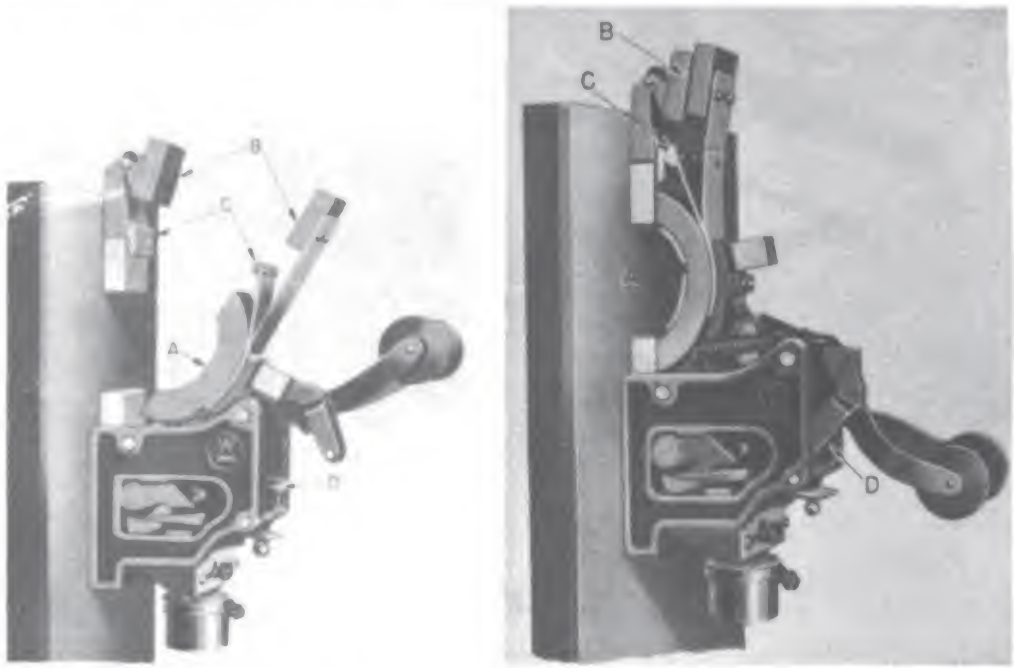


Figure 106.—Circuit breaker.

is a characteristic of nearly all circuit breakers, and nearly all operate in the same manner.

The main contact A is made of thin strips of copper curved into the form of an arc and pressed very closely together. This laminated construction of the contact permits it to close on the stationary contacts with a wiping motion and to fit evenly over the entire surface.

The auxiliary contacts *B* are called arcing contacts, both of which are provided with removable carbon tips. These contacts are carried by long copper springs.

The other auxiliary contacts, or intermediate contacts *C*, are just above the main contact. The movable part consists of a heavy copper spring with a removable copper tip.

HOW IT WORKS

When the breaker opens, the MAIN CONTACT OPENS FIRST. But NO ARC is drawn across the face of the contact because there is still a path for the current through the auxiliary contacts. Thus

the surface of the main contact is kept smooth and of low resistance in order to carry the full load current without loss.

The INTERMEDIATE CONTACT opens next. A SMALL ARC may be drawn when this contact opens because the remaining circuit through the carbon tips of the arcing contacts has a rather high resistance. But it is better to have the arc across this contact than across the main contact. The copper tip on the intermediate contact may be replaced much more easily and cheaply than the main contact.

The ARCING CONTACT opens last. The MOST SEVERE ARC is drawn at this point. But the carbon tips WITHSTAND the heat fairly well and aren't burned away as rapidly as copper. Furthermore the carbon tips are easily and cheaply replaced when they are burned too badly to be used.

When the circuit breaker closes, the arcing contacts close first, the intermediate contact next, and the main contact last.

This order of operation of the contacts upon opening and closing of the circuit breaker eliminates practically all arcing and pitting of the main contacts. The degree of protection which the auxiliary contacts give the main contacts depends upon the condition of the auxiliary contacts. It is important to keep them properly adjusted and to renew the tips occasionally.

CIRCUIT BREAKER CLOSING MECHANISM

The mechanism which closes the circuit breaker may also be seen in figure 106. The contacts are pressed into the closed position by PULLING DOWNWARD on the closing arm. The closing arm is latched in the closed position by a trigger. Notice this trigger *D* in both the open and closed views of the circuit breaker in figure 106.

When the trigger is tripped, the circuit breaker is PULLED open BY ITS OWN WEIGHT, or by a spring. Remember. both the auxiliary contacts are mounted upon heavy copper springs. These springs help to give the breaker a SWIFT and SURE action when the trigger holding the breaker closed is tripped.

A SERIES CIRCUIT BREAKER TRIP COIL

The trigger on the circuit breaker may be tripped by hand, but

it is usually done automatically. It is tripped automatically by a TRIP COIL, as shown on the circuit breaker in figure 107. The trip coil may be of either the shunt or series type. Figure 107 shows a series trip coil which consists of a FEW TURNS of HEAVY COPPER bar around an iron plunger.

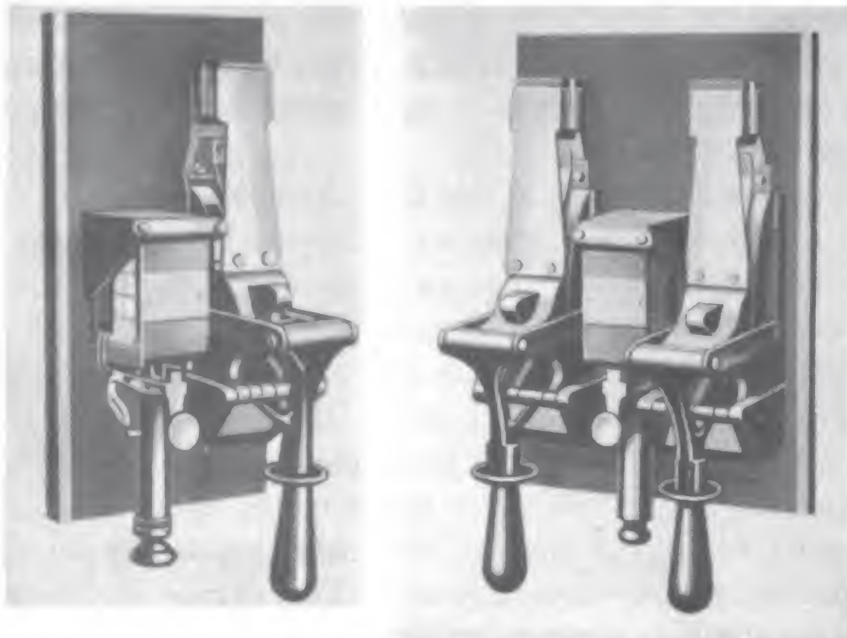


Figure 107.—A circuit breaker trip coil.

The coil is connected in series with the contacts. When the current through the circuit EXCEEDS a predetermined value, the magnetic field around the coil lifts the plunger. The plunger trips the trigger on the circuit breaker, which is thrown open.

The series trip coil is commonly used on circuit breakers up to 500 amperes capacity. Above this capacity the shunt trip coil is generally used. But don't get the idea that the shunt trip coil is used only on the higher capacity circuit breakers. IT is USED ON ALL SIZES. In fact it has several advantages over the series trip coil. With the shunt trip coil the circuit breaker may be opened and closed from REMOTE points by a control switch, a pushbutton, or a relay. It is used with circuit breakers to give protection against UNDERVOLTAGE and REVERSED current.

A SHUNT CIRCUIT BREAKER TRIP COIL

The shunt trip coil is connected across the positive and negative fuses of the main line, but the circuit is normally open and

the coil is de-energized. To trip the circuit breaker, the coil is energized by completing the circuit through it—this lifts the plunger and trips the circuit breaker.

For automatic operation, the circuit through the shunt coil is closed by an OVERLOAD RELAY, which is actuated by the MAIN LINE CURRENT. It isn't connected to carry the main line current, but is connected across an AMMETER SHUNT placed in the circuit. Or it may be connected across a section of bus bar or cable with the same resistance as the ammeter shunt.

The voltage drop across the ammeter shunt varies directly with the load current. So, if the coil of the relay is connected across the ammeter shunt, the voltage drop across the coil will vary with the load current. However, this voltage drop across the ammeter shunt is very low, usually a few milli-volts. So the overload relay is very sensitive and is designed to operate on 50 to 100 milli-volts.

The overload relay is designed to operate when the line current exceeds a predetermined value. When the current exceeds this value, the voltage drop across the relay coil causes the relay to operate and close the circuit to the shunt trip coil. The trip coil operates and trips the circuit breaker.

A circuit breaker which opens automatically when an overload occurs on the circuit is called an OVERLOAD CIRCUIT BREAKER.

UNDERVOLTAGE CIRCUIT BREAKERS

An undervoltage circuit breaker is designed to open if the voltage fails or falls below a SAFE VALUE. This circuit breaker may be the SAME KIND that is used for overload protection, but the TRIPPING DEVICE IS DIFFERENT. As a matter of fact, both undervoltage and overload protection may be incorporated in the same circuit breaker.

The undervoltage tripping device is built in such a manner that its magnetic coil pulls the plunger AWAY from the trigger of the circuit, or circuit breaker. The plunger is pulled toward the trigger by a spring. As long as the voltage across the coil is NORMAL, the magnetic pull of the COIL IS GREATER than the pull of the spring. Thus the plunger is held AWAY from the trigger of the circuit breaker. But when the voltage fails or falls

below a predetermined value, the pull of the SPRING IS GREATER than the magnetic pull of the coil and the plunger is lifted against the trigger. The circuit breaker is tripped and the circuit is opened.

REVERSE CURRENT CIRCUIT BREAKERS

By putting a reverse current relay in the circuit of the trip coil, the circuit breaker may be made into a reverse current circuit breaker. That is, it opens the circuit ONLY in case of a reverse current. Overloads do not cause it to open.

The trip coil is shunt wound and its circuit is controlled by a REVERSE CURRENT RELAY. The reverse current relay consists of two elements or windings which react upon each other in a manner similar to the reaction of the field and armature of a motor. One element is called the POTENTIAL or VOLTAGE COIL, and the other is called the CURRENT COIL.

The POTENTIAL COIL, connected directly across the positive and negative busses, maintains a constant field flux. This coil is stationary.

The CURRENT COIL is movable and is connected across an ammeter shunt in the load line. The direction of current through the current coil depends upon the direction of the current through the ammeter shunt. As long as the current is in the NORMAL DIRECTION, the coil tends to turn in a direction which holds the relay contacts open. This keeps the shunt trip coil of the circuit breaker de-energized. But if the current through the ammeter shunt is REVERSED, it is also reversed through the current coil of the relay. The coil tends to move in a direction that CLOSES the relay contacts. When the relay contacts are closed, the shunt trip coil is energized and the circuit breaker is tripped open.

The reverse current relays may be adjusted to operate at the desired amount of reverse current.

Reverse current circuit breakers are used on naval vessels in connection with storage battery operation, especially on CHARGING PANELS. They are also used in PARALLELING generators.

Circuit breakers may be of single, double, or triple pole construction. Figure 106 shows the single pole type and figure 107

shows a double pole type. Circuit breakers aboard naval vessels are built so that they are not liable to trip when subjected to successive heavy shocks, as from gunfire. They are designed to operate on voltages between 125 and 500 volts and with capacities ranging from 15 to 6,000 amperes.

BRAKES FOR D.C. MOTORS

Motors used to drive winches, capstans, and anchor windlasses are equipped with AUTOMATIC BRAKES. On some jobs the brakes are used only to stop and hold the load. On other jobs the brakes are used for lowering loads.

The WATERPROOF SOLENOID BRAKE shown in figure 108 is typical of the automatic brakes used to stop and hold loads. The brake wheel *K* is keyed to the shaft of the motor. The brake shoes *G* are pressed against the brake wheel by the spring *M* acting through rod *F*. The braking torque is determined by the tension of the spring. A SOLENOID, located in the watertight housing *J*, is connected to carry all or a part of the armature

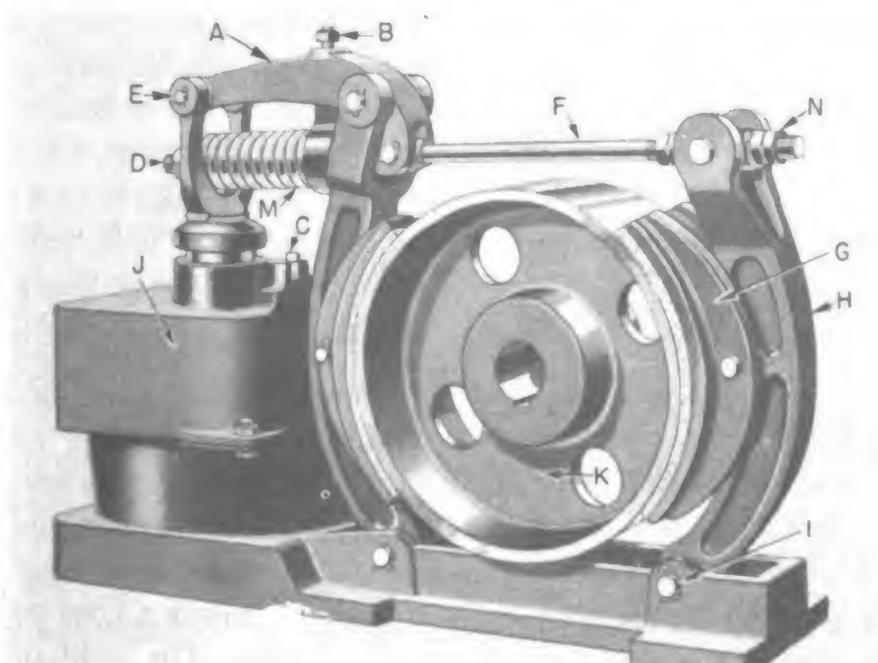


Figure 108.—Waterproof solenoid brake.

current. When current is applied to the motor, the solenoid is energized and pulls the iron plunger downward. This pulls

the brake liner *A* downward. The resulting lever action on the rod *F* and the brake arm *H* pushes the brake shoes apart, compresses the spring *M*, and relieves the brake pressure.

If the current to the motor is CUT OFF or FAILS, the SOLENOID IS DE-ENERGIZED. The compressed spring applies the brake pressure immediately. The motor is stopped quickly, and the load is held until the motor is started again.

The solenoid. plunger is designed to travel a very short distance. But as the brake shoes wear, the travel distance increases. This travel distance must be compensated for by shifting the adjusting nut *N* on the connecting rod *F*.

The brake shoe clearance is equalized by the adjusting nut shown at *C*. The braking torque is regulated by adjusting the nut at *D*. *B* is the mechanical release mechanism.

DYNAMIC BRAKING

DYNAMIC BRAKING is especially suitable on motors used for lowering loads. Figure 109 is a schematic diagram of a motor connected for dynamic braking.

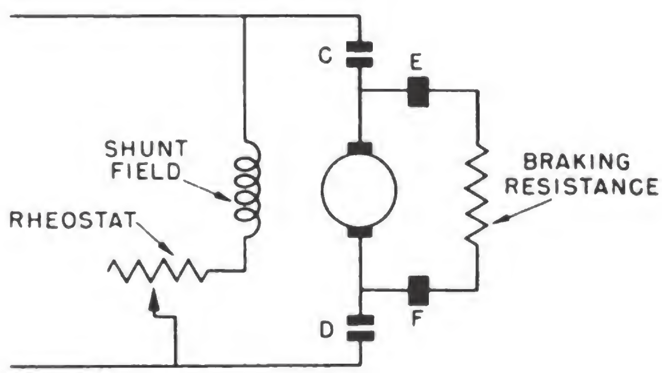


Figure 109.—Dynamic braking circuit.

When the ARMATURE is disconnected from the line by contactors *C* and *D*, the contactors *E* and *F* connect a LOW RESISTANCE directly across the armature brushes. The field is connected across the line.

The load on the motor will tend to keep the armature rotating in the magnetic field. An emf is induced in the armature windings and a high current flows through the armature and breaking resistance. The MOTOR armature then acts as a GENERATOR.

You know that IT REQUIRES POWER TO DRIVE A GENERATOR ARMATURE. So, when the load of the brake resistance is placed across the motor armature, it absorbs the energy of the load which tends to keep the armature rotating. This brings the armature to a smooth, quick stop. Or when a motor is being used to lower a load, it PREVENTS the load from OVERHAULING the motor. By varying the braking resistance or the field strength, the effect of the dynamic braking is controlled.

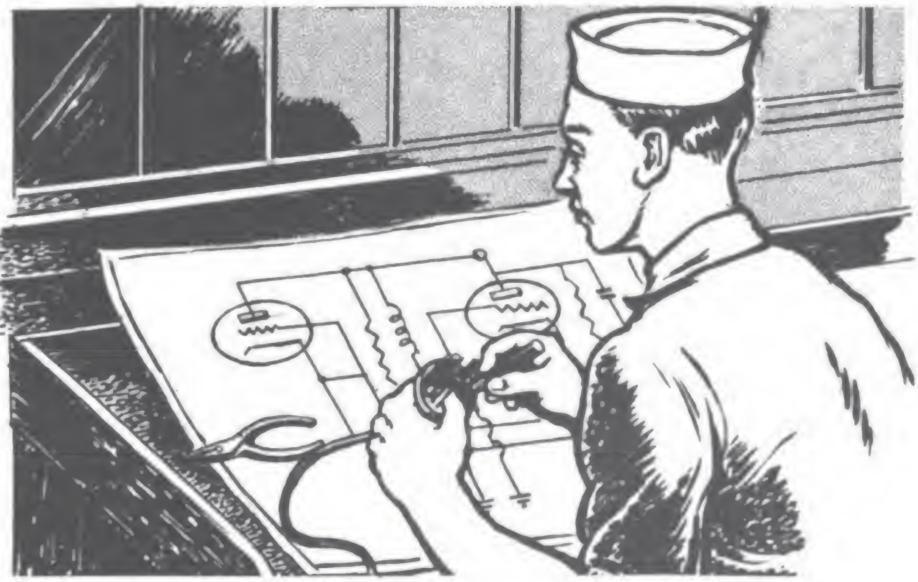
Another way of explaining the effect of dynamic braking is as follows. You have learned that the counter emf produced by a motor is in the OPPOSITE DIRECTION to the applied voltage. When the armature is disconnected from the line and connected ACROSS the braking resistance, the load tends to keep it rotating. It is rotating in the same direction as the magnetic field and in the field. So an emf, that has the same direction as the counter emf, is induced in the armature windings. This emf causes a HIGH CURRENT to flow through the armature and the starting resistance in the direction opposite to the direction that the line current flowed.

Since the current is in the OPPOSITE DIRECTION to the direction of the line current, and the polarity of the field hasn't changed, it will tend to drive the armature in the opposite direction. But when the armature reaches a complete stop, no emf is induced in its conductors and no current flows. This results in a cushioning effect and provides one of the smoothest forms of braking which can be used on d.c. motors.

To obtain dynamic braking when a drum controller is used, another set of segments and contacts is provided. When the drum controller is rotated to the STOP position, these segments and contacts connect the field across the line and connect the braking resistance directly across the armature brushes. This braking resistance MAY be a part of the starting resistance.

On automatic contactor panels, additional contactors are used. These contactors close and place the resistance across the armature brushes when the line contactors open.

When dynamic breaking is used on series motors, a resistance must be put in series with the series field before it is connected across the line.



CHAPTER 13

ALTERNATING CURRENTS

WHERE THEY ARE USED

Since 1934 the first line Navy ships have used alternating current for general lighting, for power, and for certain interior communication circuits. Some ships have propulsion motors powered by a.c.

Although d.c. is still more desirable for some jobs, a.c. has several advantages over d.c. for many purposes. The advantages, as well as disadvantages, will be discussed later. First you should know the main characteristics which distinguish a.c. from d.c.

WHAT IS A.C.?

A DIRECT CURRENT flows in only ONE DIRECTION and in most cases it has a constant value for definite periods of time. An ALTERNATING CURRENT is constantly changing in magnitude, and its direction changes at regular intervals. Be sure you understand that last statement—AN ALTERNATING CURRENT IS CONSTANTLY CHANGING IN MAGNITUDE, AND ITS DIRECTION CHANGES AT REGULAR INTERVALS.

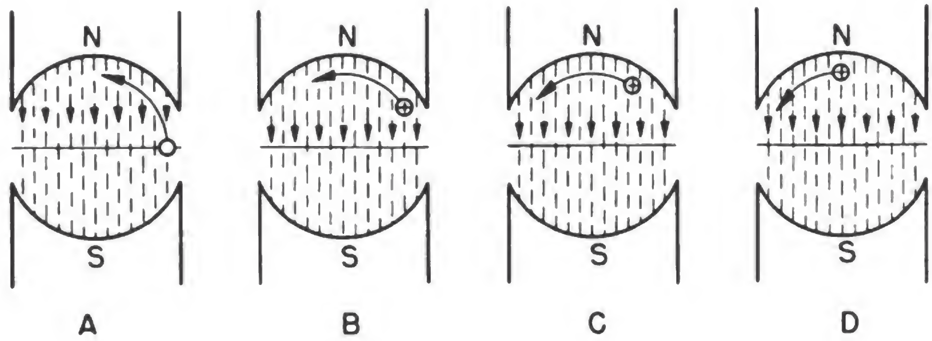


Figure 110.—Rotation of a coil in a stationary flux.

To understand an alternating emf more thoroughly, picture a single coil side (figure 110) rotating at a constant speed in a uniform magnetic field.

WHY IS A.C. CONSTANTLY CHANGING?

By using the generator hand rule and studying figure 110, you can prove that the emf changes its direction at regular intervals. As the conductor goes through the half revolution while it is under the north pole, the induced emf is in one direction. As the conductor goes through the other half revolution, under the south pole, the induced emf is in the opposite direction.

When the conductor is at postion A, it is moving PARALLEL to the field and is CUTTING NO FLUX LINES. At position *D*, the conductor is moving ACROSS the flux field at a 90° angle and cutting flux at the MAXIMUM rate. But at position *B*, 30° from position *A*, the conductor is moving more nearly parallel to the field than at *D*. And even though the conductor is moving at the same speed at *B* and *D*, it is NOT CUTTING FLUX as RAPIDLY at *B* as at *D*. Likewise at *C*, 60° from *A*, you can see that the conductor is not cutting flux lines as rapidly as at *D*, but is cutting them more rapidly than at *B*.

Thus as the conductor moves from *A* to *D*, the rate at which it cuts flux lines INCREASES and is proportional to the angle through which the conductor has moved from the horizontal. For the next quarter revolution, the rate of cutting flux DECREASES from a maximum to zero. For the last half revolution the PROC-

ESS is REPEATED, but the conductor cuts the flux lines in the OPPOSITE DIRECTION.

How does all this affect the emf?

Remember that the emf induced in a conductor is DIRECTLY PROPORTIONAL to the RATE at which the conductor cuts magnetic flux lines. Thus the emf induced in the coil side shown in figure 110, at any instant, depends upon the ANGLE at which the coil side is cutting the flux lines. From this explanation you can see why the emf induced in the coil side is CONSTANTLY CHANGING as the coil side is rotated in the field. This also explains why the current changes its direction at regular intervals.

An alternating emf increases from ZERO to MAXIMUM and decreases to ZERO in one direction, during the first half revolution. Then it goes through the same set of values in the opposite direction, during the second half revolution.

GENERATION OF AN ALTERNATING VOLTAGE

You have just seen how an emf is induced in a coil when it is rotated in a magnetic field. Figure 111 illustrates graphically

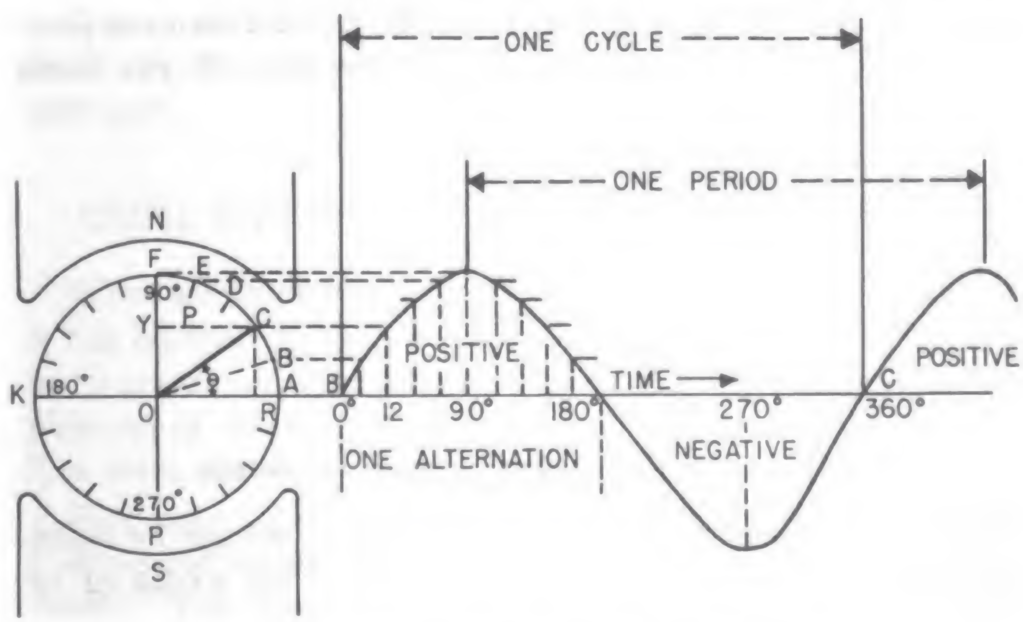


Figure 111.—Alternating current, single phase.

the voltage generated by a simple two-pole, single-coil generator during one complete revolution.

The line *OP* represents the end view of one-half of the re-

volving coil. When the coil is in position A*a*, the conductor, perpendicular to *OP* and extending back into the page, is moving parallel to the lines of force. Therefore, the current or voltage generated is zero. As the coil rotates away from *a*, the conductor cuts lines of force faster and faster until position *f*, 90° from the original position, is reached.

Now draw a straight line such as *BC* and mark-off on it equal angular positions. Then draw horizontal lines from the different positions of *P* at *b, c, d, e, f*, etc., until they intersect the vertical lines from the line BC. This gives you a picture of the voltage generated and of the current which is flowing in the rotating coil at each position of *P*. A figure constructed in this manner is known as a SINE CURVE, or sine wave. The shape of the voltage wave of a properly constructed generator is in actual practice very close to that shown in figure 111.

INSTANTANEOUS VOLTAGES

The instantaneous voltage is the emf at ANY POINT on the SINE CURVE of the ALTERNATING emf. It depends upon the POSITION of the coil with RESPECT to the zero position along the time axis at any instant. In easier words, it is the VOLTAGE present at any INSTANT during a cycle of rotation. If you know

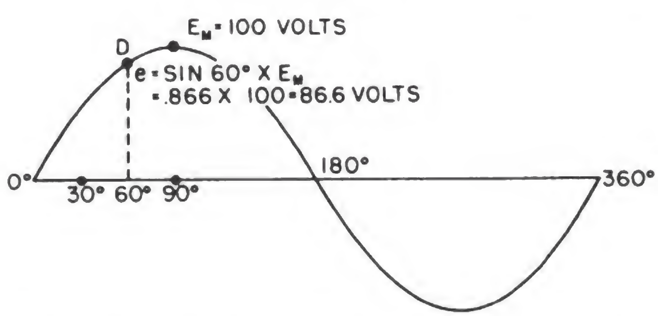


Figure 112.—Instantaneous values of a.c. voltage.

trigonometry, you can find the instantaneous voltage by multiplying the MAXIMUM voltage by the SINE of the ANGLE of rotation.

For example, assume the maximum value of the emf sine wave in figure 112 is 100 volts. The instantaneous value at point *D*, 60° of rotation, on the curve is—

$$e = E_{max} \times \sin 60°$$
$$e = 100 \times .866 = 86.6 \text{ volts.}$$

The half of the sine wave above the time axis represents voltage in one direction, and the half below the time axis represents voltage in the opposite direction. The half of the sine wave above the axis is called the POSITIVE part of the alternating emf, and the half below the time axis is called the NEGATIVE half.

ELECTRICAL DEGREES vs. MECHANICAL DEGREES

You are familiar with the term mechanical degrees. You know that if a coil is rotated through a complete revolution it travels 360°—mechanical degrees. But it doesn't necessarily travel through 360*E*°—electrical degrees.

Each time a conductor passes BOTH a NORTH and a SOUTH POLE in an alternator, it has traveled 360E°. Thus, during one complete revolution in a TWO-POLE alternator, a conductor travels 360 MECHANICAL degrees and 360 ELECTRICAL degrees. However, during one complete revolution in a FOUR-POLE alternator a conductor travels 360 MECHANICAL DEGREES but 720 ELECTRICAL DEGREES—360E° for each pair of poles.

During your study of a.c., remember that a conductor has to pass only TWO MAGNETIC poles to travel 360E°—180E° for each pole.

CYCLE AND FREQUENCY—WHAT DO THEY MEAN?

When a coil completes one revolution in a two-pole alternator, it has traveled 360E°. It has passed a pair of poles—a north and a south—and the generated emf has passed through a complete set of values as indicated by the SINE WAVE in figure 113. The wave then repeats itself each revolution.

Each time the voltage goes through a complete set of values, positive and negative, it has completed a CYCLE and has traveled 360E°. The TIME required to complete one cycle is called a PERIOD.

When the voltage completes HALF a cycle, or 180E°, it has gone through one ALTERNATION. Thus the voltage goes through an alternation when the COIL PASSES ONE POLE. And, the number of alternations is TWICE the number of cycles.

The number of cycles completed in one second is known as the FREQUENCY of a voltage. Frequency is generally expressed as so many cycles, meaning so many cycles per second. Thus, you

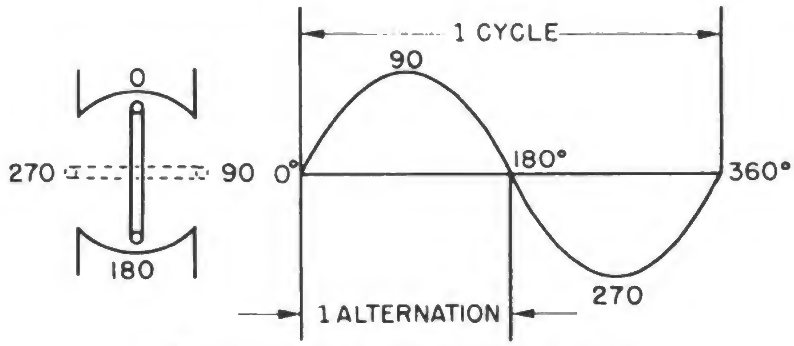


Figure 113.—Alternation vs. a cycle.

would say, "The frequency of the voltage is 60 cycles," meaning the voltage completes 60 cycles each second.

WHAT DETERMINES THE FREQUENCY OF A VOLTAGE?

To answer this question use the four-pole alternator in figure 114. Each time a coil makes a complete revolution in this alternator it passes two pairs of poles and goes through 720E°. When a coil passes a pair of poles—a north and a south—it goes through 360E° and completes one cycle. Therefore, for ONE COMPLETE ROTATION of a coil in this four-pole alternator, the

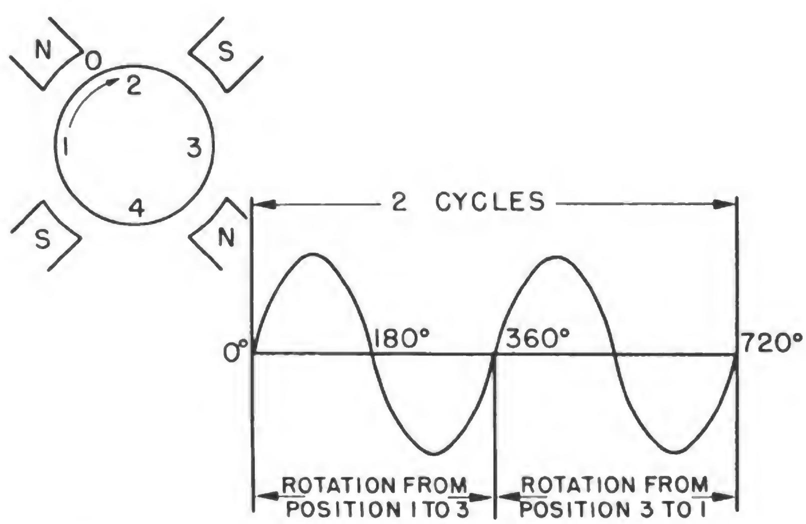


Figure 114.—Frequency with a four-pole alternator.

voltage completes TWO CYCLES. Thus, the number of cycles per revolution is equal to the number of poles in the alternator divided by two—

$$\text{cycles per rotation} = \frac{2}{\text{poles}}$$

The FREQUENCY—cycles per second—equals the number of cycles per revolution multiplied by the revolutions per second. If the coil in a four-pole alternator makes 60 r.p.s.—revolutions per second—the frequency is—

$$\frac{4}{2} \times 60 = 120 \text{ cycles.}$$

The speed is usually given in revolutions-per-minute, so if you divide rpm's by 60 you get rps. Then for an alternator with *P* poles and the speed *S*, the formula for frequency is—

$$f = \frac{P \times S}{2 \quad 60} \text{ or}$$

$$f = \frac{PS}{120}$$

where

$$\frac{2}{P} = \text{number pairs of poles}$$

$$S = \text{speed in rpm.}$$

Apply the formula to the following examples—

What is the frequency of the emf generated in a FOUR-POLE alternator operating at 1,800 rpm?

$$f = \frac{4 \times 1{,}800}{120} = 60 \text{ cycles}$$

What must the RPM of an eight pole alternator be to produce a 60 cycle emf?

$$f = \frac{PS}{120}$$

therefore—

$$S = \frac{120f}{P}$$

$$S = \frac{120 \times 60}{8} = 900 \text{ rpm}$$

An alternator operating at 3,600 rpm produces a 60 cycle voltage. How many poles does the alternator have?

$$f = \frac{PS}{120}$$

therefore—

$$P = \frac{120f}{S}$$

$$P = \frac{120 \times 60}{3{,}600} = 2 \text{ poles}$$

MEASURING ALTERNATING CURRENTS AND VOLTAGES

If an a.c. voltage is applied to a closed circuit, an a.c. current will flow. The current will vary in amount and change directions

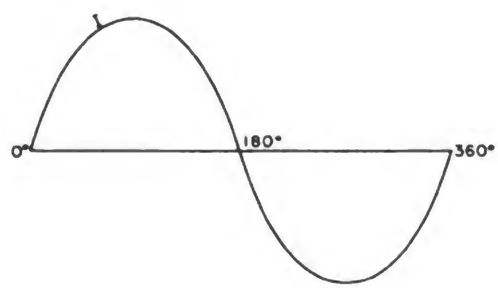


Figure 115.—A sine wave of alternating current.

just as the voltage does. The alternations in current can be shown as a SINE WAVE, figure 115, just as a.c. voltage can be shown as a sine wave.

The question naturally arises—What is the value in amperes of this wave, and how is it measured?

EFFECTIVE VALUES

The EFFECTIVE VALUES of alternating current and voltage are based upon HEATING EFFECT. An AMPERE of alternating current is produced by an ampere of direct current.

It is obvious that an alternating current which has a MAXIMUM VALUE of one ampere is NOT going to produce the same CONTINUOUS HEATING effect as a direct current which has a constant value of one ampere. The continuous EFFECTIVE VALUE of the alternating current is going to lie somewhere BETWEEN ZERO and its MAXIMUM value. The EFFECTIVE VALUE IS ALWAYS LESS THAN THE MAXIMUM VALUE.

At first thought it might seem that the effective value in amperes would be the average of the instantaneous values of an alernation. But, that ISN'T THE CASE.

The effective value is based on HEATING EFFECT of current which varies as the SQUARE of the CURRENT—that is, it is proportional to I^2R. Therefore, the average heating effect of an alternation varies as the average of the squares of the instantaneous values of the current during the alternation. This heating effect is positive regardless of the direction of current, and will be the same for the positive and negative alternations of the cycle.

Since the effective value in amperes of an alternating current is based upon the heating effect, you find the effective value in amperes of an alternation by finding the SQUARE ROOT of the average of the squares of all instantaneous values. That means you square a number of EQUALLY SPACED instantaneous values throughout the alternation. Add the squares, and divide by the number of instantaneous values used. Then take the square root of the quotient. This is called the ROOT-MEAN-SQUARE—usually written RMS.

An interesting thing about the RMS problem just explained is that the EFFECTIVE voltage is ALWAYS 0.707 times the MAXIMUM or PEAK voltage. Many times you will find the effective voltage stated as the RMS voltage.

If the RMS method is used on an alternating current which has a maximum value of one ampere, the effective value will be found to be 0.707 amperes. Therefore—

$$I_{eff} = I_{max} \times 0.707$$

$$I_{max} = \frac{I_{eff}}{0.707} = I_{eff} \times 1.41$$

where— I_{eff} = effective current
I_{max} = maximum current

Thus, if an alternating current has a maximum value of 10 amperes, it has an effective value equal to—

$$0.707 \times 10 = 7.07 \text{ amp.}$$

In other words an alternating current with a maximum value of 10 amperes will produce the same amount of heat as a direct current of 7.07 amperes.

Similarly, the EFFECTIVE VOLTAGE is—

$$E_{eff} = E_{max} \times 0.707$$

$$E_{max} = \frac{E_{eff}}{0.707} = E_{eff} \times 1.41$$

Fortunately you don't have to do these calculations to find effective values everytime you use a.c. All a.c. instruments are calibrated to read the EFFECTIVE VALUES unless otherwise specified. And when alternating current of voltage values are specified, they are ALWAYS effective values unless there is a definite statement to the contrary.

Here's a point to remember when determining the insulation for an a.c. circuit. The voltage given for the circuit is effective value, but the insulation must withstand the MAXIMUM VALUE of each alternation. That means if the voltage given for the circuit is 450 volts, the insulation must withstand a maximum of 634 volts—450 $\times$ 1.41—each alternation.

PHASE

Figure 116*A* shows the sine waves for an a.c. voltage E and the current I that is caused to flow in a circuit. The curves have the same scale in degrees along the horizontal TIME LINE, but they have separate individual maximum values along the vertical axis. Notice how the current and voltage pass through their maximum and zero values at the SAME time. This current is said to be IN PHASE with the voltage.

Figure 116*B* shows an a.c. voltage and the current which it causes to flow in a given circuit. In this case, the current DOES NOT pass through its maximum and zero values at the same time the voltage passes through its maximum and zero values. The current and voltage are OUT OF PHASE. The current passes through its maximum values 45° LATER than the voltage, and

the current is said to LAG the voltage by 45°. Why does the current lag the voltage? That will be explained later.

Figure 116C shows a.c. current which passes through its zero and maximum values AHEAD of the voltage. The current and voltage are OUT OF PHASE, the current leading the voltage by 45°

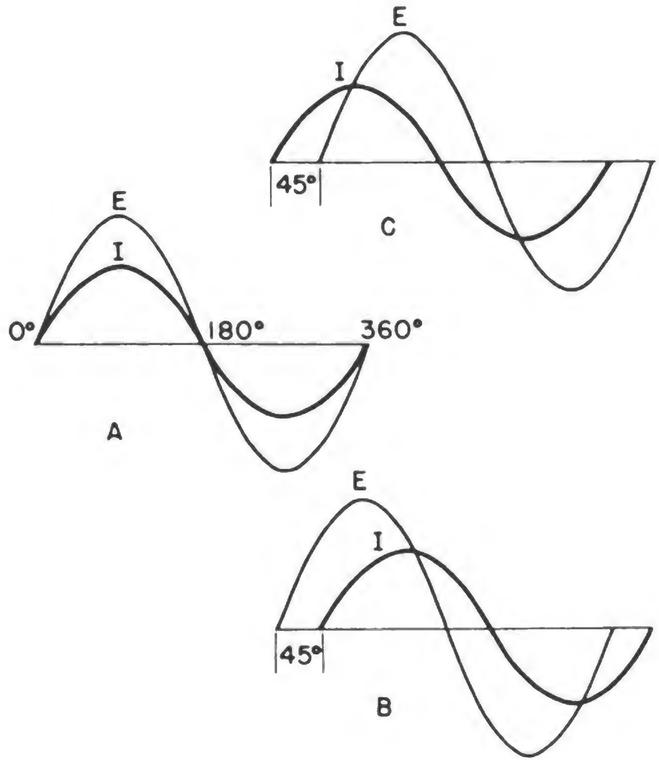


Figure 116.—Phase relationships.

In each of the above illustrations, the term PHASE is used to designate the TIME DIFFERENCE—expressed in ELECTRICAL DEGREES—between an a.c. voltage and its current. PHASE is used also to designate time difference—expressed in electrical degrees—between a.c. voltage of the same frequency, or between a.c. currents of the same frequency.

ADDING A.C. QUANTITIES

The motors of a ship are driving it north at 12 knots. The wind is driving the ship east at five knots. At the end of an hour, how far has the ship traveled?

There are two forces acting on the ship. But it is apparent that the result of the two forces cannot be found by merely adding them together arithmetically, because the forces ARE NOT acting in the SAME DIRECTION. The direction of forces is just as important as the amount of force.

You learned from Basic Mathematics that VECTORS are used to represent scale. Draw the vector OA, figure 117, to represent the distance the ship is driven toward the NORTH by the motors, Draw vector OB to represent the distance the ship is driven toward the EAST by the wind. Vector OB is drawn at right angles to OA because the force of the wind is at RIGHT ANGLES to the force of the motors of the ship.

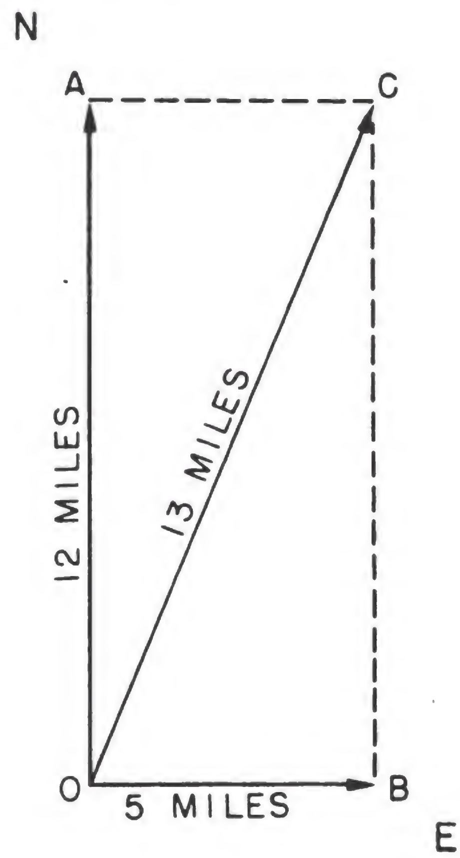


Figure 117.—Vector diagram showing a resultant of two forces.

It is obvious that the ship cannot be at both points A and B, But it will be at a point 12 miles north and five miles east of O. That point is C. And the distance and direction the ship has traveled—13 miles—is represented by the vector OC. The dis-

tance can be found by measuring the line OC and using the same scale that was used for drawing OA and OB.

It can also be found by using the TRIANGLE METHOD for adding the vectors. That is, the distance traveled by the ship would be—

$$OC = \sqrt{(OA)^2 + (OB)^2}$$

or

$$OC = \sqrt{12^2 + 5^2} = 13 \text{ miles}$$

USING VECTORS TO ADD VOLTAGES

Figure 118 shows the sine waves of two a.c. voltages, E' and E'', which are 90° out of phase. Here you have two forces acting

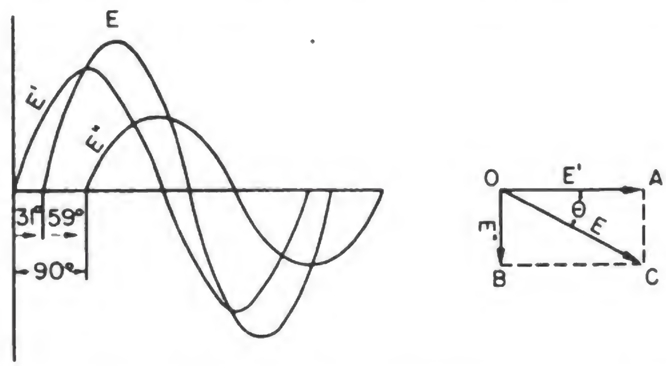


Figure 118.—Vector addition of two voltages 90° out of phase.

at an angle of 90° from each other. They cannot be added arithmetically. However, they can be added vectorially, just as you added the two forces acting on the ship.

Vector OA is drawn to represent voltage E'. Vector OB is drawn at an angle of 90° to OA, to represent voltage E''. The two voltages are added vectorially, and the resultant vector OC is the vectorial sum E, of E' and E''.

The angle θ represents the phase difference between E and E'. The resultant voltage E lags the voltage E' which is represented by the horizontal vector.

Example—Each of two alternator coils OA and OB, figure 119A, is generating an emf of 120 volts. The voltages have a phase difference of 90°. What is the voltage across their open ends if they are connected together at O as shown? See figure 119B.

Draw vector $O'A'$ to represent the voltage across coil OA. Draw vector $O'B'$ at right angles to $O'A'$ to represent the voltage across coil OB. Add the two vectors. It can be seen that the resultant voltage is the vector $O'C$, which is also the hypotenuse of a right triangle with sides $O'A'$ and $O'B'$. Therefore, the resultant voltage is—

$$E_{o'e} = \sqrt{120^2 + 120^2} = 169.2 \text{ volts.}$$

OUT OF PHASE CURRENTS are added vectorially in the same manner as out of phase voltages.

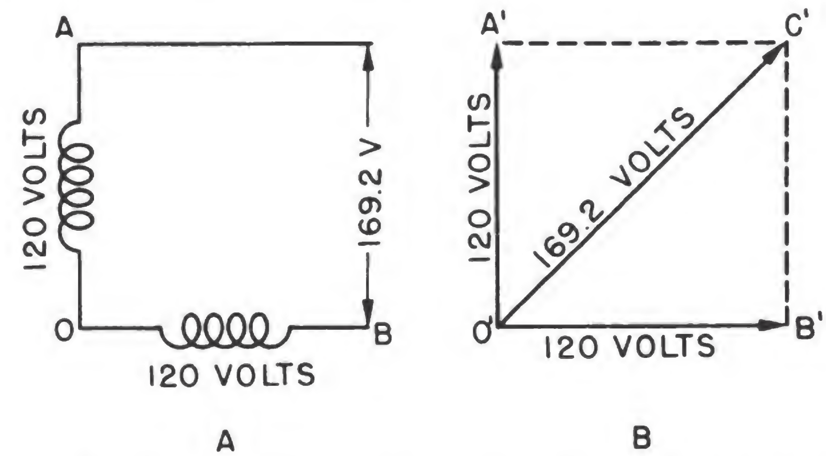


Figure 119.—Vector addition of two equal voltages 90° out of phase.

When two voltages or two currents are IN PHASE they may be added ARITHMETICALLY. If they are 180° out of phase, they are in opposite directions, and their total is the ALGEBRAIC sum.

IT MUST BE KEPT CONSTANTLY IN MIND THAT ALTERNATING CURRENTS AND VOLTAGES MUST BE COMBINED VECTORIALLY.

CHAPTER 14

REACTANCE

LIKE A HIDDEN RESISTANCE

An experiment was performed in which one winding of a transformer was connected to a 10 volt d.c. supply. The current was 20 amperes. When the same winding was connected to a 2,500 volt a.c. supply, the current was 1.82 amperes!

Why did 10 volts d.c. cause 20 amperes to flow in the circuit, but 2,500 volts a.c. cause only 1.82 amperes to flow?

At first it may seem that somewhere in the experiment Ohm's Law was repealed. But it wasn't. Ohm's Law applies to a.c. as well as d.c. circuits, but you need to know more about Ohm's Law and a.c. circuits to find the answer to the experiment.

In the case of the 10 volt d.c. supply, the opposition to the flow of current is just the ohmic resistance. And if 20 amperes flowed, the resistance would be—

$$R = \frac{E}{I} = \frac{10}{20} = 0.5 \text{ ohm.}$$

But in the case of the 2,500 volt a.c. supply and a 1.82 ampere current, the opposition is—

$$Z = \frac{E}{I} = \frac{1.82}{2{,}500} = 1375 \text{ ohms.}$$

Z is the symbol for IMPEDANCE measured in ohms.

IMPEDANCE may be defined as the TOTAL OPPOSITION to the

flow of current in an a.c. circuit. Then Ohm's Law for an a.c. circuit is—

$$I = \frac{E}{Z}$$

In the case of the transformer, the impedance is considerably greater than the ohmic resistance. This is true in most a.c. circuits. The additional opposition is caused by inductance or capacitance in the circuit, and is called REACTANCE. The symbol for reactance is X, which is measured in ohms.

INDUCTANCE IN AN A.C. CIRCUIT

You learned in d.c. that INDUCTANCE is the property of a circuit which opposes any change in the current. That is, if the current increases, the expanding flux field cuts across the conductor and induces a voltage which opposes the increase in current. But if the current decreases, the flux lines collapse and cut across the conductor in the opposite direction. This induces a voltage which tends to keep the current flowing in the same direction.

Of course this effect is small in a straight wire. But if the circuit is in the form of a coil, the effect is much greater—the circuit is said to have more inductance. An iron core placed in the coil increases still further the inductance of the circuit. From this you can see that the inductance of a circuit is directly related to the physical properties of the circuit.

Many d.c. circuits, such as the shunt field of a motor, are highly inductive. But this inductance affects the current only when there is a change of current in the circuit.

The unit of inductance is the HENRY, for which the symbol is L. A circuit has an inductance of one henry if a current change rate of ONE AMPERE PER SECOND will cause a cemf of ONE VOLT to be induced in the circuit.

Figure 120*A* shows the effect of inductance on a d.c. current in a circuit which has several henries of inductance and a given resistance. When a voltage is applied to the circuit, the current flow is equal to the voltage divided by the resistance. But the current does not reach this value immediately. It increases

gradually from zero to its normal value. This increase is gradual because of the back emf induced by the expanding flux field. Once the current reaches the value determined by the voltage and resistance, it is no longer affected by the inductance of the circuit, unless there is another change in current.

When the circuit is broken, the current does not fall to zero immediately, but decreases gradually as shown in figure 120*B*.

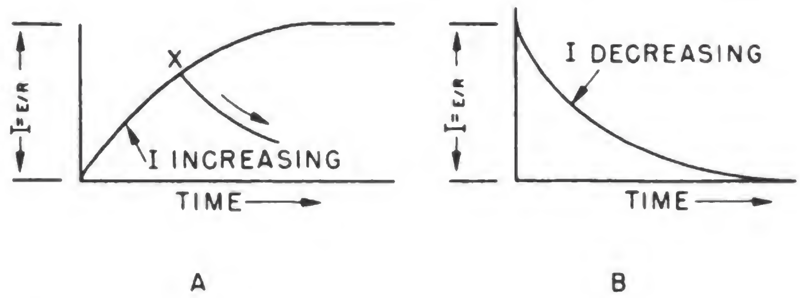


Figure 120.—Increase and decrease of a d.c. current in an inductive circuit.

As the current decreases, the collapsing flux field induces an emf which tends to keep the current flowing.

The time required for the current to go from zero to its normal value, or to go from its normal value to zero, is determined by the INDUCTANCE of the circuit. Thus, a d.c. current will reach its normal value in a straight wire quicker than in a solenoid.

Suppose you closed the circuit and the current began to increase as shown in figure 120*A*; but then you opened the circuit when the current reached point *X* on the curve. The current would never reach its Ohm's Law value. The same effect occurs in an a.c. circuit. The current does not have time to reach its Ohm's Law value before the voltage begins to decrease. So—the CURRENT NEVER REACHES ITS OHM'S LAW VALUE IN AN A.C. CIRCUIT CONTAINING AN INDUCTANCE.

Furthermore the tendency of the inductance to oppose any change in current will cause the current to reach its maximum values and minimum values behind the voltages.

BACK EMF IN AN INDUCTANCE

The constantly changing a.c. current induces a BACK EMF

which is constantly opposing any change in the current. This back emf may be compared to the counter emf in a d.c. motor. Thus, you can see that in addition to the opposition to the flow of current which results from ohmic resistance, there is an OPPOSITION CAUSED BY THE EMF OF SELF-INDUCTION.

The higher the inductance of the circuit, the more concentrated the flux field; and the higher the frequency, the faster the flux lines cut the conductors. Therefore, the emf of self-induction is directly proportional to the INDUCTANCE of the circuit and to the FREQUENCY of the current.

This opposition to the flow of current caused by inductance in an a.c. circuit is called INDUCTIVE REACTANCE. It is expressed in OHMS and its symbol is X_L.

HOW TO FIND THE INDUCTIVE REACTANCE

The inductive reactance of an a.c. circuit may be found by the formula—

$$X_L = 2\pi f L$$

Where—

X_L = inductance reactance expressed in ohms.
$2\pi = 2 \times 3.1416 = 6.2832$
f = frequency
L = inductance in henries.

Figure 121 shows a circuit containing 0.4 henry of inductance. It is connected across a 220 volt, 60 cycle line. What is the reactance, and how much current will flow?

$$X_L = 2\pi f L = 2\pi \times 60 \times 0.4 = 150.8 \text{ ohms}$$

$$I = \frac{E}{X_L} = \frac{220}{150.8} = 1.46 \text{ amperes.}$$

If the frequency is doubled, the X_L is doubled and the current I is cut in half. Or, if the inductance is doubled by increasing the number of turns, the X_L is doubled and the current is cut in half. Thus you see that in an inductive circuit the a.c. current varies inversely as the frequency of the current and the inductance of the circuit.

Figure 122*B* is a vector diagram of the phase relationship between current and voltage in a circuit without resistance. The

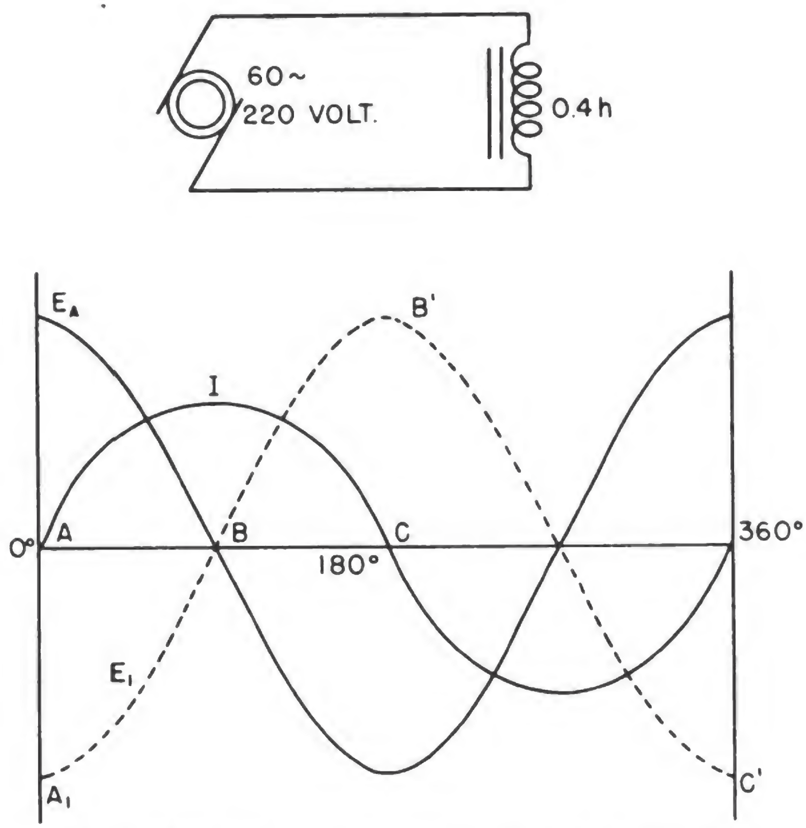


Figure 121.—Circuit containing an inductance only.

current, shown along the horizontal axis, LAGS behind the voltage by 90°.

You understand that it is impossible to have a circuit that contains no resistance. The resistance was ignored in this circuit to avoid confusion. Solutions of circuits containing both X_L and R will be explained later.

Summing up—inductance opposes any change in the current flowing in a circuit. The amount of inductance in a circuit depends upon the physical properties of the circuit, that is, the number of turns, the length of coil, and the kind of material used in the core.

Inductance in an a.c. circuit causes the current to lag the voltage.

WHY DOES THE CURRENT LAG THE VOLTAGE?

The sine wave *I* in figure 121 represents the current flowing in a circuit containing only inductance. At point *A*, the current is changing at its MAXIMUM RATE in a positive direction. So,

at that instant the EMF of SELF INDUCTION must be at its MAXIMUM value in negative direction.

As the current increases from zero to maximum the RATE OF CHANGE DECREASES. Therefore, the emf of SELF INDUCTION DECREASES. At point *B* the current has reached its maximum value and for an instant the rate of change is zero and at that instant the emf of self induction also must be zero.

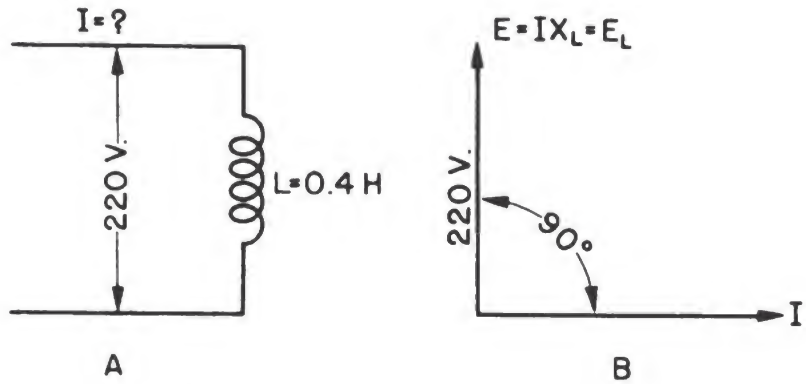


Figure 122.—Vector diagram of circuit containing inductance only.

The current then begins to decrease from its maximum value toward zero and the flux begins to collapse. The emf of self induction begins to build up in the OPPOSITE direction. At *C*, the current is again changing at a maximum rate but in a NEGATIVE DIRECTION; so, at that instant, the emf of self induction must be a maximum in the positive direction. Continuing in this way the voltage curve *A'B'C'* is obtained for the emf of self induction. Because of the voltage of self induction, the current is caused to lag by 90°.

This emf of self induction is the ONLY VOLTAGE in the circuit which OPPOSES the current. There must be an applied voltage and the voltage of self induction in the OPPOSITE DIRECTION. The APPLIED VOLTAGE sine wave is drawn 180° out of phase with the sine wave of the voltage of self induction. Notice that the applied voltage curve LEADS the current *I* by 90°, which is another way of describing the same phase relationship.

In a circuit with inductance only and no resistance that is what would happen. Actually, it is impossible to obtain a purely inductive circuit, because every circuit must necessarily have

some resistance. However, the resistance may be so small it is negligible.

CAPACITANCE

CAPACITANCE is the ability of a circuit to store up electrical energy in the form of an ELECTRIC CHARGE. The CONDENSER is the device used to give the circuit capacitance.

Essentially, the condenser consists of two metal plates separated by an insulator called a dielectric. The CAPACITY or ability of a condenser to hold a charge is determined by the number of plates, the exposed surface area, the material of the dielectric, and the thickness of the dielectric.

Figure 123 is a diagram of a two-plate condenser. The terminals of the condenser are connected through a switch to a

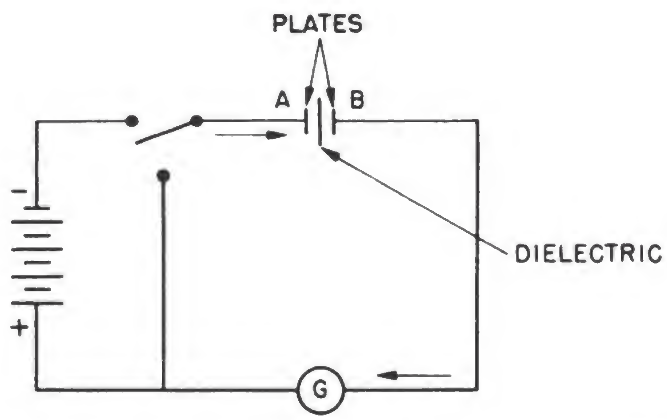


Figure 123.—Charging a condenser in a d.c. circuit.

battery. When the switch is closed, the DIFFERENCE in POTENTIAL between the two battery terminals puts an electromotive force upon the electrons of the circuit. They start to move FROM the NEGATIVE terminal of the battery TOWARD the POSITIVE terminal. They cannot pass through the dielectric because the voltage isn't high enough to break the electrons free in the dielectric material. Thus negative charge is built up on plate *A* of the condenser.

The electrons of the dielectric are repelled by this negative charge on the plate *A*, and have a tendency to move toward the

opposite side of the dielectric. In other words, the side of the dielectric next to plate *A* has a tendency to become positively charged and the other side tends to become negatively charged. Electrons are not broken free in the dielectric, but they do move toward the positive terminal of the battery, causing plate *B* to become POSITIVELY CHARGED.

A galvanometer placed in the circuit will indicate this shift in electrons. Thus, there is an APPARENT FLOW of current through the condenser when the circuit is first closed. Actually there isn't, because the voltage isn't high enough to break down the dielectric. But there is a MOMENTARY SHIFT of electrons. The plates of the condenser are charged—one negatively and the other positively—and the dielectric is in a STATE OF STRAIN.

Now, if the condenser is disconnected from the battery, the plates retain their charge. The length of time they will hold this charge depends upon several factors, and may range from a few seconds to several hours.

However, if the terminals of the condenser are shorted together by a good conductor, the electrons on plate *A* will rush to plate *B* until the charge between the two plates is EQUALIZED. And a galvanometer in the circuit will indicate a flow of current in the direction opposite to that which was indicated when the condenser was charged.

Now, put a switch in the circuit which can alternately open and close the battery circuit and short the condenser terminals. If the switch is operated rapidly, the condenser will be alternately charged and discharged, and give the effect of an ALTERNATING CURRENT while flowing between the terminals of the condenser.

Each time the switch closes the battery circuit, an emf is applied and the condenser charges. When the switch opens the battery circuit, shorting the condenser terminals, the condenser discharges.

Notice in particular that the current was maximum 90° before the voltage was maximum (figure 124). Thus you say, in a pure capacitive circuit (one without resistance) the CURRENT LEADS the VOLTAGE by 90°. Since no circuit is without resistance, the current leads the voltage by less than 90°.

On the discharge of the condenser and the charge in the opposite direction, electrons run out of one side and into the other side of the condenser in the same manner.

Remember: in a capacitive circuit, the current is always MAXIMUM BEFORE the condenser reaches FULL CHARGE.

A CONDENSER BLOCKS D.C. BUT CONDUCTS A.C.

One of the most used features of a condenser is its ability to BLOCK the flow of d.c., and to CONDUCT a.c.

When a condenser is connected into a d.c. circuit, it will become charged quickly. The flow of electrons is then stopped, and when fully charged, the condenser acts as an OPEN CIRCUIT.

A condenser connected into an a.c. circuit acts quite differently. On the positive half cycle, electrons leave one plate, flow through the generator and the load in the circuit, and back into the other plate of the condenser.

During the next negative half alternation, the electrons reverse their direction and flow out of the negative plate, through the generator, and back into the opposite plate of the condenser. After the applied emf has reached MAXIMUM in the NEGATIVE direction, the flow of electrons is again reversed, charging the condenser in the original direction again.

Each time the cycle is reversed, the electrons leave one side of the condenser and enter the other. In this way, electrons continue to flow through the circuit as long as the generator is running.

Remember, the electrons DO NOT go through the condenser. They merely run out of one side and in at the other.

A condenser is fully charged when the VOLTAGE across the condenser terminals is EQUAL to the APPLIED VOLTAGE. Regardless of the voltage applied, the condenser is not fully charged until the condenser voltage equals the applied voltage.

The flow of current in a condenser is dependent upon the DEGREE OF CHARGE present on the condenser plates. For example, suppose a discharged condenser is connected to the terminals of a 10 volt battery. The BACK EMF of the condenser at this instant is zero, so a maximum current flows.

Immediately when the current starts to flow, the condenser begins to build up a voltage of its own. This voltage—call it back emf—opposes the emf of the battery, so the flow of current is slowed down.

The longer the condenser continues to charge, the larger and larger the back emf becomes, until eventually, it equals the applied emf. When this condition is reached, all current ceases to flow, and remains that way until the condenser is discharged, or a higher emf is applied.

The RATE of CURRENT FLOW is greatest when the switch is first closed. Look at figure 124. Curve *E* represents the con-

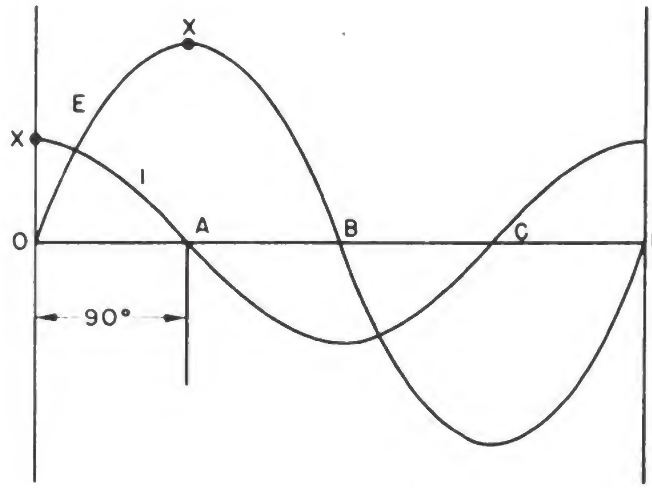


Figure 124.—Relationship of current and voltage in a capacitive circuit.

denser voltage. You may call this curve the CHARGE on the condenser. Curve *I* shows the CURRENT FLOWING.

Start at the left edge of the drawing. Point *O* shows the condenser voltage the instant the switch is closed. Notice it is equal to zero. Now look at point *X*, above point *O*. It shows the current flowing the instant the switch is closed. The current at this instant is maximum.

Immediately after closing the switch, look what happens to both current and voltage. The RATE of CURRENT FLOW goes DOWN, and the CHARGE goes UP. When the charge reaches maximum at point *X*, the current flow at point A is zero.

SIZE OF A CONDENSER

The capacity of a condenser to store an electrical charge is a property of the condenser's physical structure, and depends on the exposed surface area and material of the plates, the

distance between them, and the type of dielectric used. The unit used to express capacity is the FARAD. It is the capacity of a condenser that is capable of having a COULOMB of displaced electrons with an applied emf of only ONE VOLT.

A condenser with a capacity of one farad would be as large as a good-sized compartment, and would have little practical value. So, capacities are usually expressed in MILLIONTHS of a farad, ONE MICROFARAD is equal to $\frac{1}{1,000,000}$ of a farad. A capacity of 50 microfarads, abbreviated 50 mf., is equal to $\frac{50}{1,000,000}$ farads.

CAPACITIVE REACTANCE

The amount of alternating current that can flow in a circuit containing a condenser depends upon both the capacity of the condenser, and the frequency of the applied voltage. The a.c. flowing in a circuit varies directly as the capacity and frequency. Therefore the larger the condenser and higher the frequency, the lower will be the opposition to the flow of current.

The opposition to the flow of an alternating current by a capacitive circuit is called CAPACITIVE REACTANCE, like the opposition of inductive reactance. Capacitive reactance is expressed in ohms. Thus, Ohm's Law for a pure capacitive circuit may be expressed—

$$I = \frac{E}{X_c}$$

where X_c is the capacitive reactance expressed in ohms.

Since current increases as the C and f increase, X_c must decrease at a rate inversely proportional to C and f. This relationship is expressed in the following formula—

$$X_c = \frac{1}{2\pi fC}$$

where—

X_c = capacitive reactance in ohms
2π = 6.2832

f = frequency
C = capacitance in farads

Since the farad is much too large a unit for practical use the equation may be rewritten for the microfarad—

$$X_c = \frac{10^6}{2\pi f mfd}$$

X_c = capacitive reactance
10^6 = 1,000,000
2π = 6.2832
f = frequency
mfd = capacitance expressed in microfarads

Example—A condenser of 25 microfarads capacity is connected to a 240 volt, 60 cycle supply. What is the reactance and how much current will flow?

$$X_c = \frac{10^6}{2\pi \times 60 \times 25} = 106 \text{ ohms}$$

$$I = \frac{E}{X_c} = \frac{240}{106} = 2.50 \text{ amperes}$$

CHAPTER 15

IMPEDANCE

WHAT IS IMPEDANCE?

The IMPEDANCE to the flow of an alternating current in a circuit is the combined oppositions of RESISTANCE, INDUCTIVE REACTANCE, and CAPACITIVE REACTANCE. All circuits have resistance, but not all have inductive and capacitive reactance. Some have inductive reactance, others have capacitive reactance with resistance, but the combination of either or both reactances with resistance forms the IMPEDANCE of the circuit.

You remember how it was impossible to add directly two voltages that were out of phase. You added them VECTORIALLY. The same thing is true of combining RESISTANCE with REACTANCE. You can not add them directly, because they are in DIFFERENT DIRECTIONS.

As an example of this, resistance has no effect on the phase of the current. That means, in a resistive circuit, the current increases as the voltage increases. But how about other circuits? In an inductive circuit, the current lags the voltage, while in a capacitive circuit, the current leads the voltage.

In an INDUCTIVE circuit containing a RESISTANCE, the current still LAGS the voltage, but not by 90°. The amount of lag de-

pends upon the RATIO of the RESISTANCE to the INDUCTIVE REACTANCE.

The same thing is true in a CAPACITIVE circuit containing a RESISTANCE. The amount of LEAD is dependent upon the RATIO of RESISTANCE REACTANCE.

How great will be the lag or lead? How great the impedance. First find out what the impedance and lag will be in an inductive circuit.

IMPEDANCE IN AN INDUCTIVE CIRCUIT

Since both the resistance R and the inductive reactance X_L opposes the current, the total opposition or impedance Z will be a combination of R and X_L. The equation for finding the impedance Z of an inductive circuit is—

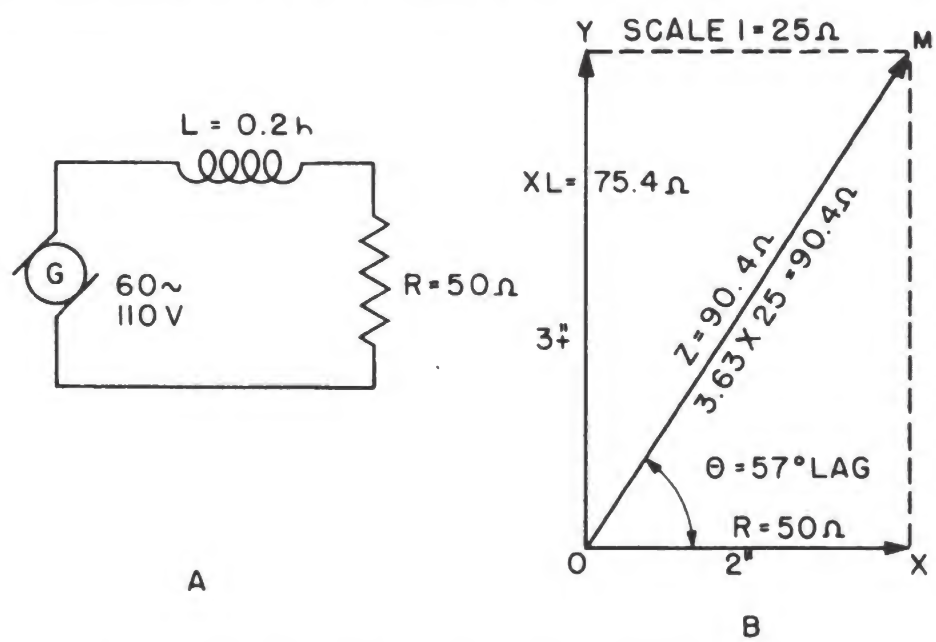
$$Z = \sqrt{R^2 + X_L^2}$$

where—

R is the d.c. ohmic resistance

X_L is the inductive reactance

Here is a problem. In figure 125A the coil has an inductance L of 0.2 henries and is attached to a 60 cycle, 110 volt generator. The resistance R of the circuit is 50 ohms.



Figur. 125.—Solution of an inductive reactance problem.

First find X_L by using the equation—

$$X_L = 2\pi f L$$

substituting—

$$X_L = 2 \times 3.14 \times 60 \times 0.2$$
$$X_L = 75.4 \text{ ohms}$$

Now use the formula for impedance and substitute.

$$Z = \sqrt{50^2 + 75.4^2}$$
$$Z = 90.4 \text{ ohms approximately.}$$

You can also use a vector diagram like figure 125*B*; in the scale used, one inch equals 25 ohms.

Lay off the resistance on the horizontal line *OX*. That line will be two inches long. Now draw *OY* perpendicular to *OX*. It will be slightly longer than three inches. Complete the rectangle and draw the diagonal *OM*. Line *OM* represents the impedance *Z*. Measure it and multiply it by scale. The impedance is slightly more than 90 ohms.

What about the current? The total opposition is the impedance *Z* of 90.4 ohms. Substituting in Ohm's Law—

$$I = \frac{E}{Z}$$

$$I = \frac{110}{90.4}$$

$$E = 1.2 \text{ amp.}$$

HOW TO FIND THE ANGLE OF LAG

Look back at figure 125*B*. The angle θ formed by the lines *OM* and *OX* is the ANGLE of LAG. Measure this angle and you will find it to be near 57°. What does it mean? It means the current reacnes a maximum value of 57° after the voltage was maximum.

If you know how to use trigonometry tables, you can find the angle of lag θ, without constructing a parallelogram by using the formula—

$$\tan \theta = \frac{X_L}{R}$$

Substituting the values of *X*? and *R* from figure 125 you get—

$$\tan\theta = \frac{75}{50}$$

$$\tan\theta = 1.500$$

$$t\theta = 57^\circ \text{ approximately.}$$

Either method is correct. It saves a little time to use trigonometry.

IMPEDANCE OF A CAPACITIVE CIRCUIT

The method used to find the IMPEDANCE Z in a CAPACITIVE CIRCUIT is the same as finding the impedance in an inductive circuit, with one exception. Remember the current leads the voltage in a capacitive circuit.

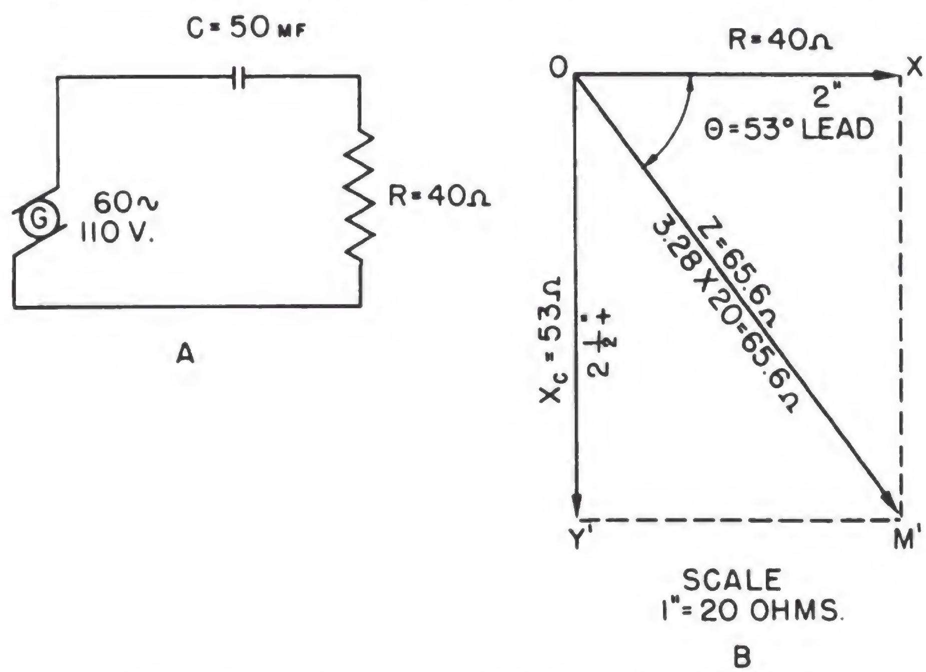


Figure 126.—Solution of a capacitive reactance circuit.

Here is a problem: A condenser of 50 mf. is connected in series with a 60 cycle, 110 volt generator. The total resistance of the circuit is 40 ohms. Find the reactance, the impedance, current and the angle of lead.

First find the capacitive reactance X_c by using the formula—

$$X_c = \frac{10^6}{R\pi fmf}$$

Substituting,

$$X_c = \frac{10^6}{6.28 \times 60 \times 50}$$

$$X_c = 53 \text{ ohms.}$$

Next find the impedance by using the equation—

$$Z = \sqrt{R^2 + X_c^2}$$

$$Z = \sqrt{40^2 + 53^2}$$

$$Z = 66.5 \text{ ohms.}$$

The current flowing will be—

$$I = \frac{110}{66.5}$$

$$I = 1.65 \text{ amperes.}$$

You can also find the impedance of the circuit by constructing a parallelogram like figure 126*B*. The only difference between it and figure 125*B* is the DIRECTION of X_c. Notice it is drawn DOWNWARD, opposite to that of X_L. That is natural, because in a capacitive circuit the current leads, and the lead angle must be in the opposite direction.

Measure angle θ, and you'll find the LEAD ANGLE is 53°. Know what that means? Sure, the CURRENT is maximum 53° BEFORE the voltage is maximum.

You can also find θ by using trigonometry and the following formula—

$$\tan \theta = \frac{X_c}{R}$$

$$\tan \theta = \frac{53}{40}$$

$$\tan \theta = 1.322$$

$$\theta = 53^\circ$$

CIRCUITS CONTAINING INDUCTANCE AND CAPACITANCE

Suppose a circuit contains both an INDUCTANCE and a CONDENSER. What happens then? You already know part of the answer. The inductance causes the current to LAG, and the condenser causes the current to LEAD.

Now if one current is lagging and the other leading, the TOTAL current certainly isn't the sum, so it must be the DIFFERENCE.

Since the IMPEDANCE of a circuit is determined by the resistance combined with the reactances, and the effect of X_L on the current is the opposite of X_c, the combined equation will be—

$$Z = \sqrt{R^2 + (X_L - X_c)^2}$$

Notice in particular the $(X_L - X_c)^2$ portion of the equation. Suppose X_L equals X_c. In that case—

$$X_L - X_c = O$$

So in the equation above you will have

$$Z = \sqrt{R^2 + O} \text{ or } Z = R.$$

Looks funny, but that is exactly what happens. In any series circuit containing an INDUCTANCE and CAPACITOR, when $X_L = X_c$, the only impedance in the circuit is the OHMIC RESISTANCE R.

What happens in a circuit where X_L does not equal X_c? The best way to answer that is to work a problem.

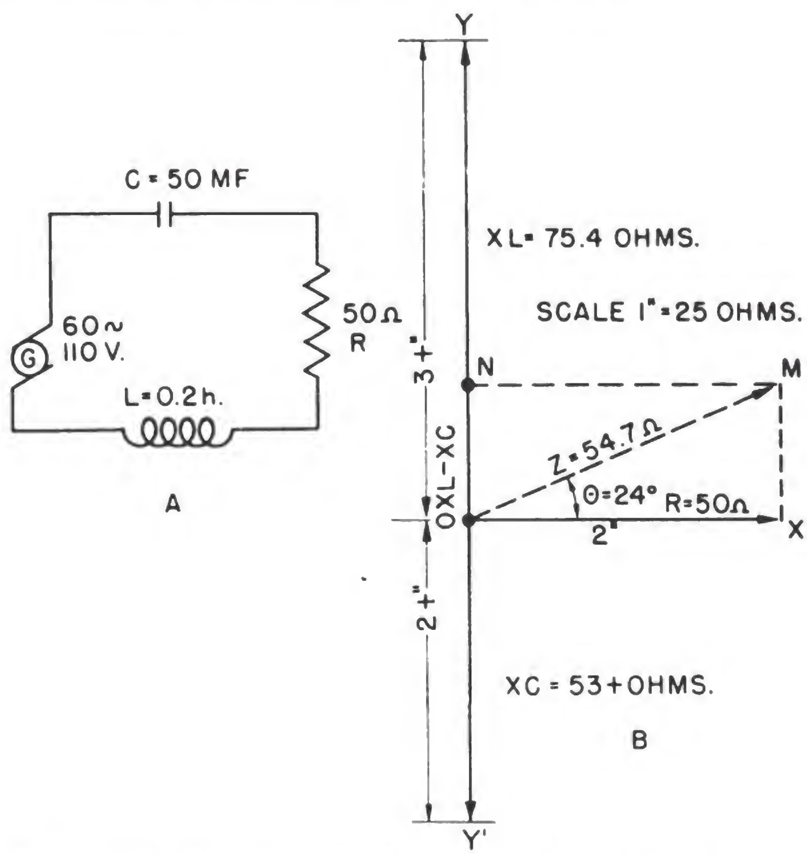


Figure 127.—Reactive circuit containing both L and c.

First find the values of X_L and X_c.

$$X_L = 6.28 \times 60 \times 0.2$$

$$X_L = 75.4 \text{ ohms.}$$

$$X_c = \frac{10^6}{6.28 \times 60 \times 50}$$

$$X_c = 53 \text{ ohms.}$$

Now substitute the values of R, X_L and X_c in the equation—

$$Z = \sqrt{R^2 + (X_L - X_c)^2}$$

$$Z = \sqrt{50^2 + (75.4 - 53.0)^2}$$

$$Z = \sqrt{50^2 + 22.4^2}$$

$$Z = 54.7 \text{ ohms.}$$

HOW TO SOLVE-L-c PROBLEMS VECTORIALLY

You can also find the impedance of the circuit vectorially as illustrated in figure 127*B*.

First draw OX equal to R, 50 ohms. It will be two inches long with a scale of one inch equal to 25 ohms. Now draw OY perpendicular to OX at O, representing X_L. Next draw OY' perpendicular to OX at O representing X_c. OY will be about three inches long and OY' about two inches long. The DIFFERENCE in OY and OY' is about one inch in favor of OY, or X_L. Then locate point N about one inch ABOVE point O. By this method you have vectorially subtracted X_c from X_L with a remainder in favor of X_L.

The only step left is to complete the parallelogram $ONMX$ and draw the diagonal OM. Measure the diagonal and multiply it by scale and you get 54.7 ohms.

Since X_L was larger than X_c, the current is still lagging. Figure 127*B* shows it to be about 24°.

You can find the angle by trigonometry—

$$\tan \theta = \frac{X_L - X}{R}$$

Substituting—

$$\tan \theta = \frac{75.4 - 53}{50}$$

$$\tan \theta = \frac{22.4}{50}$$

$$\tan \theta = .448$$
$$\theta = 24^\circ \text{ lag}$$

Don't worry if the value $X_L - X_c$ comes out to be a negative number such as—

$$\tan \theta = \frac{50 - 75}{25}$$

$$\tan \theta = \frac{-25}{25}$$

$$\tan \theta = -1.000$$
$$\theta = 45^\circ \text{ lead.}$$

That negative sign tells you the current is leading. When referring to the trigonometry table to find the angle, ignore the sign and treat the number as if it were POSITIVE.

When you solve problems vectorially in which X_c is larger than X_L, the parallelogram will be drawn below line OX, and OM will point downward. The rest of the problem is solved in the way illustrated in figure 127*B*.

So much for resistances, inductances, and condensers in series circuits. If you get stuck, go back over the problems just worked. Others are solved the same way.

SINGLE PHASE PARALLEL CIRCUITS

The most commonly encountered circuits are parallel circuits. It is, therefore, very important to know how to determine the nature of voltage and of current, through and across the various paths. The average distribution circuit has many types of loads all connected in parallel with each other—such as motors, transformers, and lighting circuits.

The solution of any parallel circuit consists of reducing it to an equivalent series circuit that, when connected to the same source of emf as the given parallel circuit, would result in the same line current and phase angle.

When several units containing resistance, reactance, or capacitance in any proportion are connected in parallel across alternating current mains, the resultant current is most readily determined by the use of vectors. You do this by solving for the current in each branch of the circuit and then combining the currents vectorially to get the resultant current.

The important distinction between the vector diagram of a parallel circuit and the vector diagram of a series circuit lies in the starting point. You will recall that in solving a series circuit you started by laying out of the vector which was common to all portions of the circuit. And in a series circuit the common vector was the current flowing through the circuit. In the case of a parallel circuit, however, the common factor for resistance, inductance, and capacitance is not the current but the voltage across each unit. Therefore, lay out as your starting point a horizontal vector pointing toward the right. This represents the voltage of the system (figure 128).

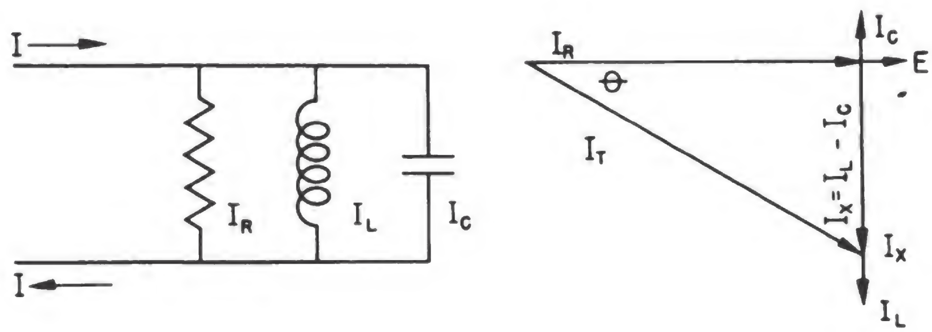


Figure 128.—A parallel circuit and vector diagram.

Since the current in a pure resistance is in phase with the a.c. voltage impressed across the terminals of that resistance, lay out the vector for the current flowing through the resistance coil along the vector of the voltage.

The next step is to lay out the current which is either 90° ahead of or 90° behind the current through the resistance. You recall that the current flowing through a condenser leads the voltage which produces that current. Therefore, the vector for the current through the condenser must be 90° away from the voltage vector and in a leading position. This is shown in figure 128 as I_C.

You also recall that the current flowing through an inductance lies 90° behind the voltage vector producing that current. Therefore, draw the vector for the current through the induct-

ance coil 90° in a lagging position behind the voltage vector as shown by I_L in figure 128.

Since the current flowing through the condenser is 180° away from the current flowing through the inductance coil, you may subtract these two values numerically. In the figure shown, the current flowing through the inductance is greater than that flowing through the condenser. Therefore, the resultant of their two currents, I_X, will be a current of a smaller value, but in the lagging position with respect to the line voltage.

The next step is to obtain the resultant between line current vector and the vector of the net current which is 90° out of phase with the line voltage. As you have previously learned, this is done by completing the parallelogram between the two vectors. The diagonal of this parallelogram is represented by I_T and the scalar length of this vector is the resultant current in the entire system, or the value of the current flowing through the main. The angular displacement between this current vector I and the voltage vector E is the phase angle of the system. The cosine of this angle—or expressed in another way, $\frac{I_R}{I_T}$ — will be the power factor of the system.

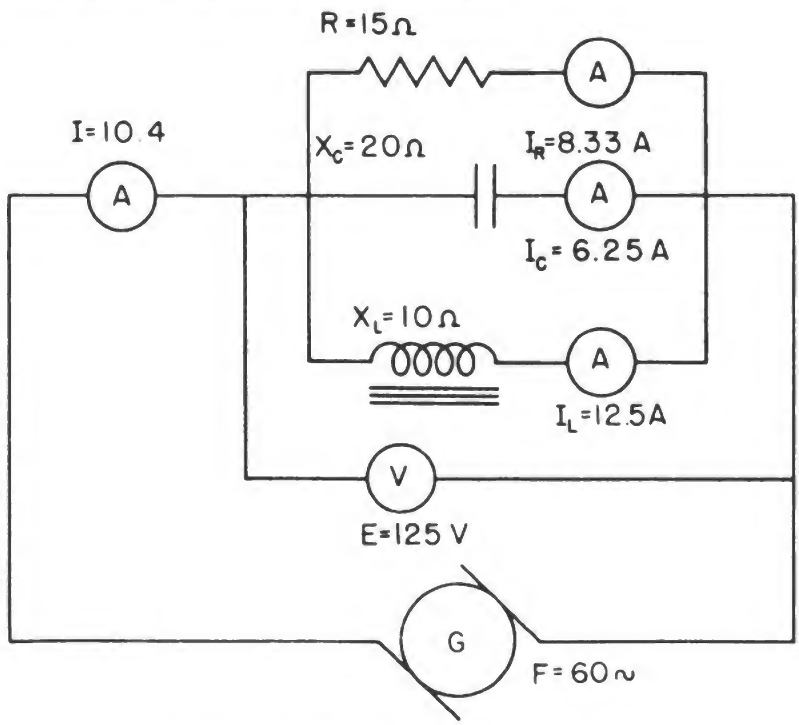


Figure 129.—A parallel circuit.

Problem: A resistance of 15 ohms, an inductive reactance of 10 ohms, and a condenser reactance of 20 ohms are all connected in parallel across a 125 volt, 60 cycle main (figure 129). Determine:

(*a*) The total current.
(*b*) The power consumed in the circuit.
(*c*) The power factor of the circuit.
(*d*) The current flowing through each portion of the circuit.

$$I_R = \frac{E}{R} = \frac{125}{15} = 8.33 \text{ amp.}$$

$$I_L = \frac{E}{X_L} = \frac{125}{10} = 12.5 \text{ amp.}$$

$$I_C = \frac{E}{X_C} = \frac{125}{20} = 6.25 \text{ amp.}$$

The above values of current can be represented by the vectors in figure 130.

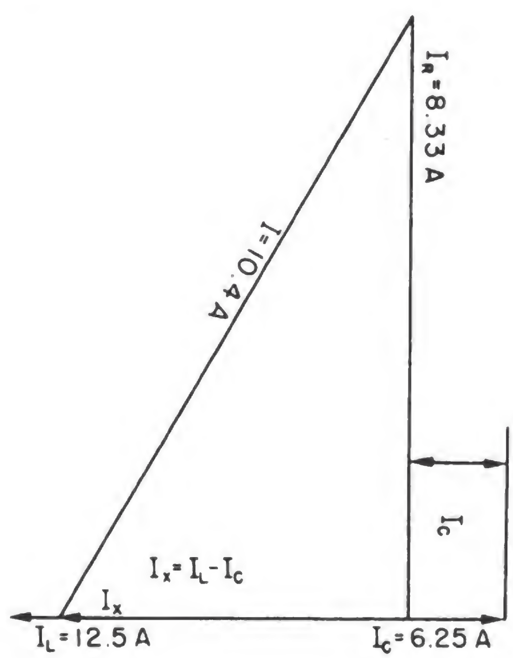


Figure 130.—A vector diagram.

The net 90° out of phase current for the above circuit = $I_L - I_C = 12.5 - 6.25 = 6.25$ amperes.

(*a*) Total amperes, $I_T = \sqrt{I_T^2 + (I_L - I_C)^2}$

$$= \sqrt{8.33^2 + (12.5 - 6.25)^2}$$

$$= \sqrt{69.5 + 39.1}$$

$$= 10.4 \text{ amperes}$$

(*b*) Power $= EI_T = 125 \times 8.33 = 1{,}041$ watts.

(*c*) Power factor, P. F. $= \cos.\text{ of } \phi = \dfrac{I_R}{I_T} = \dfrac{8.33}{10.4} = .80$ OR 80%.

(*d*) Current through the resistive path $I_R = 8.33$ amperes.
Current through the inductive path $I_L = 12.5$ amperes.
Current through the capacitive path $I_C = 6.25$ amperes.

COMPLEX SINGLE PHASE CIRCUITS REPLACING PARALLEL CIRCUIT WITH EQUIVALENT SERIES CIRCUIT

A parallel circuit may be replaced by an equivalent series circuit. This is done by solving the branch circuit as previously explained to get the value and phase angle of the line current. Once you know these values, the overall, or total, impedance for the equivalent circuit and its active and reactive components may be calculated. A circuit having these components will act electrically in exactly the same manner as the original circuit—providing the frequency of the impressed voltage is the same as that for which the calculations were made. In making the calculations, it makes no difference what voltage is impressed on the branched circuit. In the following problem, 100 volts is assumed in order to simplify the work.

For the upper branch of the circuit:

$$Z_1 = \sqrt{R_1^2 + X_1^2} = \sqrt{4^2 + 3^2} = 5 \text{ ohms}$$

$$I_1 = \frac{E}{Z} = \frac{100}{5} = 20 \text{ amperes}$$

$$\cos \phi_1 = \frac{R_1}{Z_1} = \frac{4}{5} = 0.8$$

$$\sin \phi_1 = \frac{X_1}{Z_1} = \frac{3}{5} = 0.6$$

For the lower branch:

$$Z_2 = \sqrt{6^2 + 8^2} = 10 \text{ ohms}$$

$$I_2 = \frac{E}{Z_2} = \frac{100}{10} = 10 \text{ amperes}$$

$$\cos \phi_2 = \frac{R_2}{Z_2} = \frac{6}{10} = 0.6$$

$$\sin \phi_2 = \frac{X_2}{Z_2} = \frac{8}{10} = 0.8$$

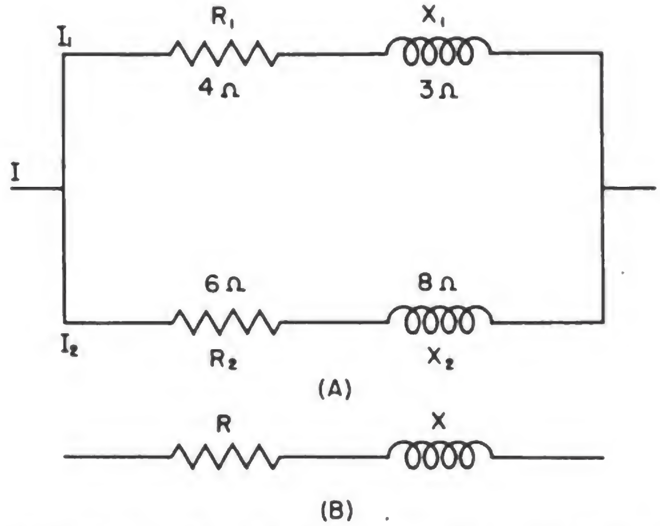


Figure 131.—A parallel circuit and its series equivalent.

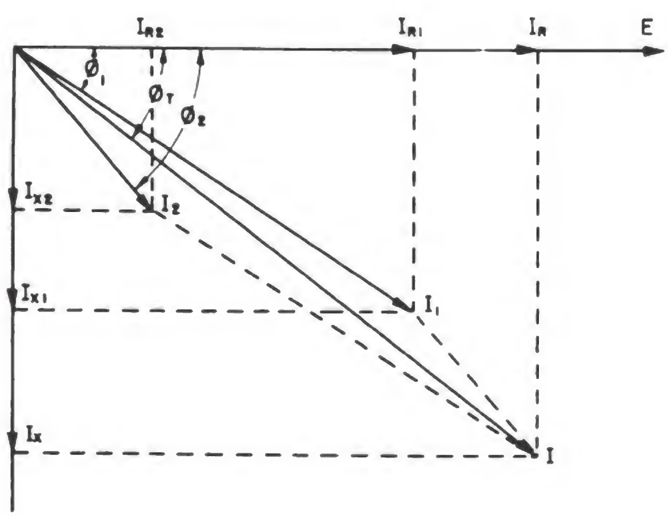


Figure 132.—The line current is the vector sum of I_1 and I_2.

Breaking down I_1 and I_2 into their active and reactive components, we have:

$I_{R_1} = I_1 \cos \phi_1 = 20 \times 0.8 = 16$ amperes

$I_{R_2} = I_2 \cos \Phi_2 = 10 \times 0.6 = 6$ amperes

$I_R =$ Sum of active components $= 16 + 6 = 22$ amperes

$I_{X_1} = I_1 \sin \phi_1 = 20 \times 0.6 = 12$ amperes

$I_{X_2} = I_2 \sin \Phi_2 = 10 \times 0.8 = 8$ amperes

$I_X =$ Sum of reactive components $= 12 + 8 = 20$ amperes

Then for the equivalent circuit:

$$I = \sqrt{I_T^2 + I_X^2} = \sqrt{22^2 + 20^2} = 29.7 \text{ amperes}$$

$$Z = \frac{E}{I} = \frac{100}{29.7} = 3.37 \text{ ohms}$$

$$\cos \phi = \frac{I_T}{I} = \frac{22}{29.7} = 0.74$$

CHAPTER 16

POWER

POWER IN A.C. CIRCUITS

The method of developing power in an a.c. circuit is similar to the way it is developed in a d.c. circuit. The POWER dissipated by a d.c. circuit is ALWAYS EQUAL to VOLTS TIMES AMPERES. But in an a.c. circuit, the power dissipated MAY or MAY NOT be equal to volts times amperes. However, AT ANY INSTANT, the power dissipated in an a.c. circuit equals the voltage at that instant multiplied by the current at that instant.

For example, figure 133 shows a current curve I in phase with a voltage curve E. THIS OCCURS IN A CIRCUIT CONTAINING ONLY A RESISTANCE.

To obtain the power taken at any instant, the current and the voltage at that instant are multiplied together. These products give the instantaneous power, and a new curve P. To construct the POWER CURVE P, find the product of the instantaneous voltage and current for several instances throughout the cycle. Plot the points indicated by the instantaneous products and draw the power curve P through these points.

The current and voltage curves pass through zero at 0°, 180°, and 360° — obviously the power at these three points will be zero. But, during the first half of the cycle, the current and voltage are both positive, so the power curve is positive. Dur-

ing the last half-cycle, the current and voltage are **BOTH NEGATIVE** so their product must be positive and the power curve is **STILL POSITIVE.**

Quite apart from this mathematical reason, it is true that the sign of the power does not change if both current and voltage are reversed. It doesn't make any difference which way the current flows in a resistance — the heat dissipated will be the same.

It should be noted that the power curve is a sine wave in shape—the axis of symmetry is line XY—with a **FREQUENCY** twice that of the current or voltage.

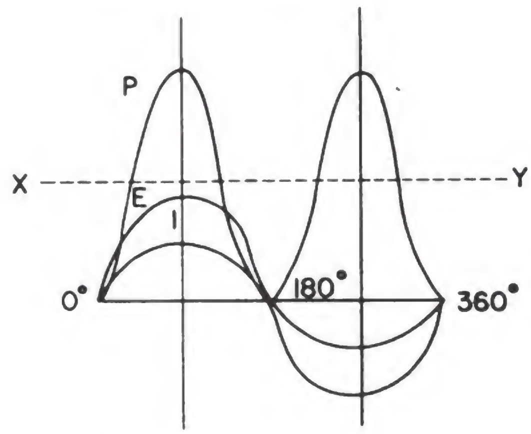


Figure 133.—Power relationships.

If the maximum values of the voltage and current waves are E_m and I_m respectively, the maximum value of the power wave must be—

$$P_m = E_m I_m$$

Since the portion above the dotted line will just fill in the portion below the dotted lines, the average of the power wave is $E_{eff} I_{eff}$. Then the AVERAGE POWER is —

$$P = E_{eff} I_{eff}$$

E_{eff} and I_{eff} equal the effective values of the voltage and current respectively. Thus, the average power in a circuit containing only resistance is —

$$P = EI$$

Remember that this formula is for power in an a.c. circuit which contains resistance only.

POWER IN A PURE INDUCTIVE CIRCUIT

Figure 134 shows the sine curves for the voltage, current, and power in an a.c. circuit containing inductance only. The current lags the voltage by 90°. Either the current or the voltage is zero at points *A, B, C, D,* and *E*. Therefore the power at each of these instances must be zero. Between *A* and *B* the CURRENT is NEGATIVE and the VOLTAGE is POSITIVE. So their product, the POWER CURVE between *A* and *B*, is NEGATIVE. That means the COIL IS DELIVERING ENERGY TO THE SOURCE OF SUPPLY.

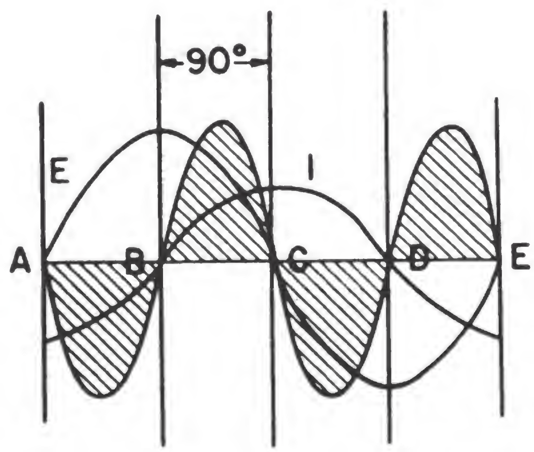


Figure 134.—Power wave for circuit containing inductance only.

Between *B* and *C* the voltage and the current are both positive. Thus the power during this period is POSITIVE. The source of supply is delivering POWER to the INDUCTANCE (coil).

Between *C* and *D* the voltage is negative, the current is positive, and the power is again negative. Between *D* and *C* the voltage and current are both negative, so the power curve is again positive.

The power curve *P* is a sine curve having double the frequency of the voltage or current. The negative area of the power curve is equal and opposite to the positive portion. This means that ALL THE POWER received by the inductance coil is RETURNED TO THE SOURCE. This is called WATTLESS POWER.

The AVERAGE POWER INPUT into the coil is zero, and a wattmeter connected in the circuit would read zero.

POWER IN A PURE CAPACITIVE CIRCUIT

Similarly, it may be shown that the power in a capacitive circuit is wattless power, and the total power consumed is zero. A wattmeter placed in a pure capacitive circuit would read zero. This isn't hard to understand. Remember that if you place only a condenser in a circuit, it will store up energy from the alternator as it is charged and return the energy to the alternator as it is discharged.

POWER IN AN INDUCTIVE-RESISTIVE CIRCUIT

If a circuit contains both inductance and resistance, the current is neither in phase nor 90° out of phase with the voltage. The current and voltage must differ in phase by an angle between 0° and 90°.

Figure 135 shows the sine curves for the voltage, current, and power in an inductive-resistance circuit. At points *A*, *B*, *C*. *D*, and *E*, either the current or the voltage is zero. Therefore, the power must be zero at these points.

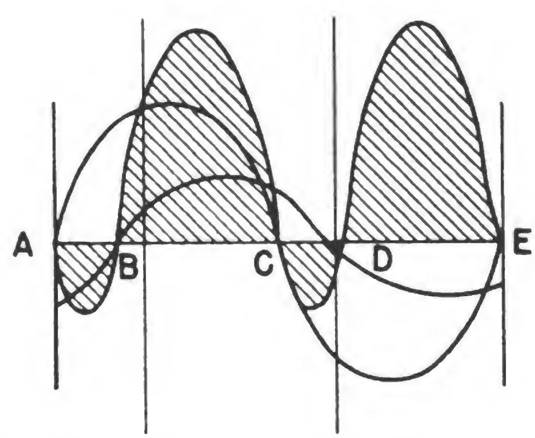


Figure 135.—Power in a resistive-inductive circuit.

Between points *A* and *B*, and between *C* and *D*, the current and voltage are opposite in working force, and the power is negative. Between *B* and *C*, and between *D* and *E*, they are in

the same direction and the power is positive. You will notice that the area under the positive part of the power curve is greater than the area under the negative part of the curve. Therefore, the AVERAGE POWER is POSITIVE but it is LESS than the PRODUCT of E and I.

APPARENT POWER AND TRUE POWER

You have learned that power in a circuit is expended by the resistance. Then—

$$P = I^2R$$

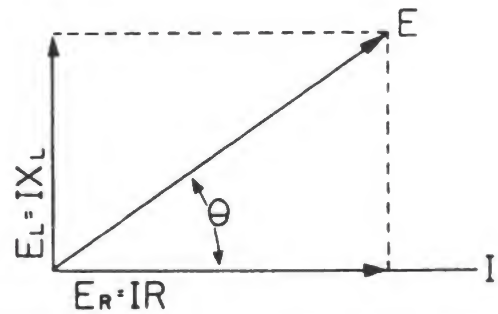


Figure 136.—Vector diagram of a series circuit containing L and R.

Figure 136 is a vector diagram of a series circuit containing inductance and resistance. By using trigonometery the following relationship is obtained—

$$IR = E \times \cos\theta$$

therefore—

$$P = I \times E \times \cos\theta = EI\cos\theta$$

where—

θ = the phase angle between voltage and current.

Cos θ = the POWER FACTOR of the circuit.

P = the TRUE WATTS or TRUE POWER.

EI = the apparent power (volt times amperes).

The power factor of a circuit is—

$$\text{P.F.} = \cos\theta = \frac{\text{true power}}{\text{apparent power}} = \frac{P}{EI}$$

So the power factor of a circuit is the RATIO of the ACTUAL POWER, true power, dissipated in the circuit to the APPARENT

POWER indicated by the product of $E \times I$. Power factor is never greater than 1.0 and is usually less than one.

Similarly, it may be shown that the power in a circuit containing RESISTANCE and CAPACITANCE in series, or resistance, capacitance, and inductance in series is the same as for an inductive-resistive circuit—

$$P = EI \cos \theta$$

In a series circuit, if X_L is greater than X_C, the current is lagging, and the circuit has a lagging power factor. If X_C is greater than X_L, the current is leading, and the circuit has a leading power factor.

Example—If a circuit containing 45 ohms resistance, 20 microfarads of capacitance, and 0.1 henry of inductance is connected across a 125 volt, 60 cycle supply, find: (*a*) the impendance of Z of the circuit; (*b*) the current I in the circuit; (*c*) the voltage E_r across the resistance; (*d*) the voltage E_l across the inductance; (*e*) the voltage X_C across the capacitance; (*f*) the power P consumed in the circuit; (*g*) the phase angle θ between the current and the line voltage; (*h*) the power factor of the circuit.

Here is the solution —

First find — $X_L = 2\pi fL = 2\pi \times 60 \times 0.1 = 37.7$ ohms.

Next — $X_C = \dfrac{10^6}{2\pi \text{ fmf.}} = \dfrac{10^6}{2\pi \times 60 \times 20} = 132.9$ ohms

Then find—

Part (*a*)

$Z = \sqrt{R^2 + (X_C - X_L)^2} = \sqrt{45^2 + (132.92 - 37.7)^2} =$ 105.3 ohms

Part (*b*) $I = \dfrac{E}{Z} = \dfrac{125}{105.3} = 1.188$ amp.

Part (*c*) $E_R = IR = 1.188 \times 45 = 53.5$ volts

Part (*d*) $E_L = IX_L = 1.88 \times 37.7 = 44.8$ volts

Part (*e*) $E_C = IX_C = 1.888 \times 132.9 = 157.8$ volts

Part (*f*) $P = I \times E_R = 1.888 \times 53.5 = 63.5$ watts

$$\text{Part (g)} \quad \tan\theta = \frac{X_C - X_1}{R} = \frac{95.2}{45} = 2\ 1155$$

$$\theta = 64.7^\circ \text{ current leading}$$

Part (h) P.F. $= \cos 64.7^\circ = 0.427$ leading.

Figure 137 shows the vector diagram for the above problem. You will notice that the voltage across the capacitance is greater than line voltage. This would indicate an error if this were a

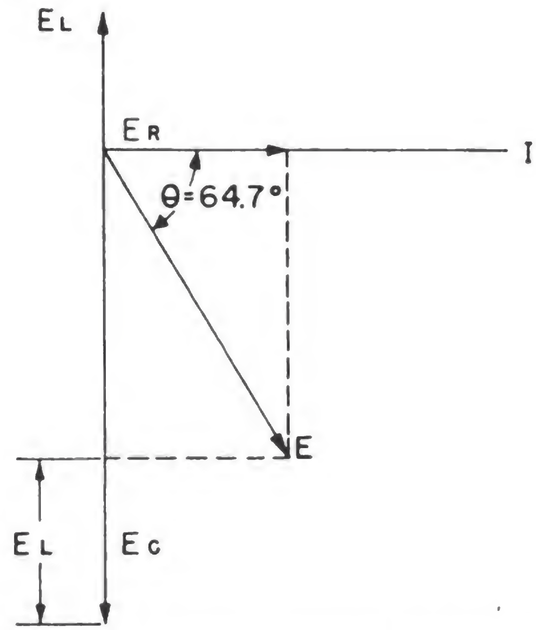


Figure 137.—Vector diagram showing leading power factor.

d.c. circuit. But in a.c. circuits, quite frequently the INDIVIDUAL VOLTAGES in parts of the circuit are GREATER than the TOTAL VOLTAGE. The reason for this is the difference in the phase relationship of the several voltages. Where a condenser and an inductance are in series in an a.c. circuit, the voltage across either or both of them may be greater than the total voltage. But, the DIFFERENCE of the two MUST BE LESS than the line voltage.

In practice, parallel circuits are more common than series circuits. The solution of problems with two or more loads in parallel is found by finding the current in each branch of the circuit and adding them vectorially to find the resultant. Of course the voltage is common to all parts of the circuit and is used as a reference vector.

The solution of a parallel circuit is illustrated by the following example—

A resistance of 10 ohms, a capacitive reactance of 8 ohms, and an inductive reactance of 15 ohms are connected in parallel across a 120 volt, 60 cycle supply as shown in figure 138*A*.

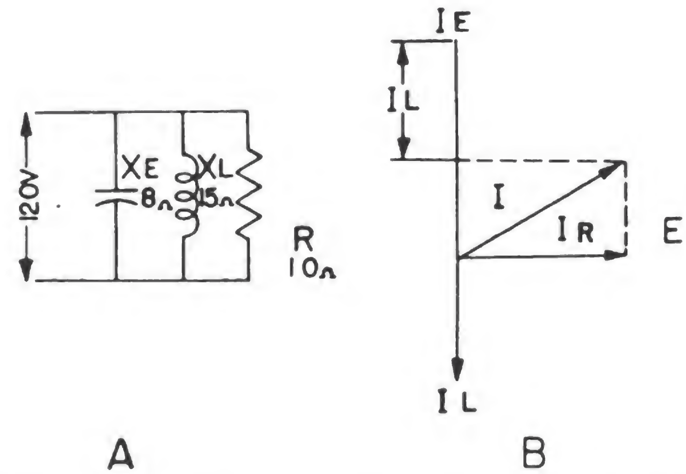


Figure 138.—Parallel L-C circuit with Vector diagram.

Find: (*a*) the total current; (*b*) the power factor of the circuit; (*c*) the power.

First, calculate the branch currents—

$$I_R = \frac{E}{R} = \frac{120}{10} = 12 \text{ amp. in phase with } E.$$

$$I_C = \frac{E}{X_C} = \frac{120}{8} = 15 \text{ amp. leading } E \text{ by } 90°.$$

$$I_L = \frac{E}{X_L} = \frac{120}{15} = 8 \text{ amp. lagging } E \text{ by } 90°.$$

These currents are shown vectorially in figure 138*B*. Adding them vectorially, the line current or total current is—

(*a*) $\mathrm{I} = 12^2 + (15 - 8)^2 = 13.9$ amp. leading.

Now, find the power factor and the power—

(*b*) $\cos\theta = \frac{\mathrm{I}_R}{I} + \frac{12}{13.9} = 0.864 = \text{P.F.}$

(*c*) $P = E \times I_R = 120 \times 12 = 1440$ watts

Also $\qquad P = EI \cos\theta = 120 \times 13.9 \times 0.864 = 1440$ watts.

From the vector diagram used in the solution of the series and parallel circuits above, it should be obvious that in a single phase a.c. circuit—

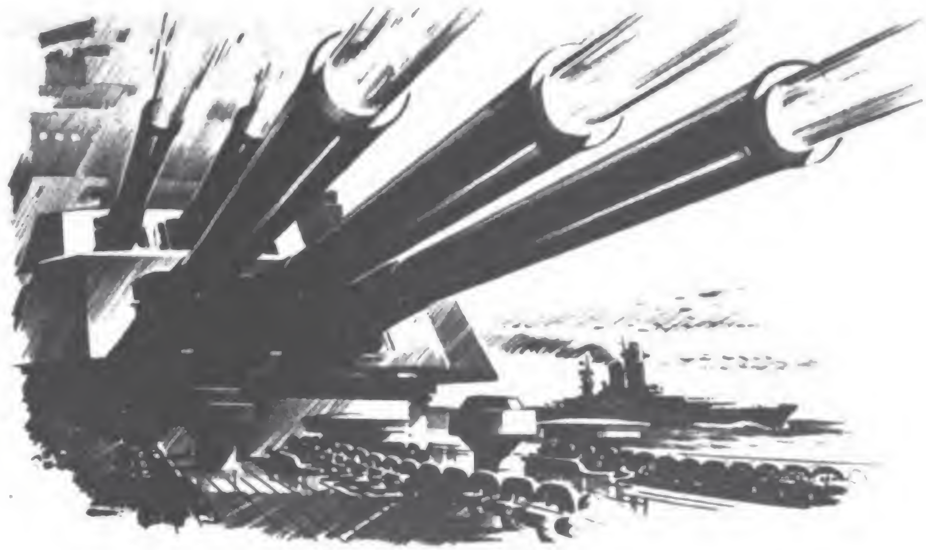
$$P = EI \cos\theta$$

the power factor is—

$$\text{P.F.} = \cos\theta = \frac{P}{EI} = \frac{\text{true power}}{\text{apparent power}}$$

and,

$$\text{P.F.} = \cos\theta = \frac{R}{Z}.$$



CHAPTER 17

ALTERNATING CURRENT GENERATORS

GENERAL PRINCIPLES

In a d.c. generator a commutator is used to change the generated emf to a d.c. voltage. If slip rings are used instead of the commutator, alternating current will be supplied to the external load. In this case the machine is called an ALTERNATOR.

The fundamental principle for the generation of an emf in an alternator is the same as in a d.c. generator. That is, the generation of emf in an armature conductor depends only on a RELATIVE MOTION between the CONDUCTOR and the FLUX FIELD. The flux field may be stationary and the armature rotated, or the armature may be stationary and the field rotated.

In practically all d.c. generators, the field is stationary and the armature is rotated. But in practically all alternators, the armature is stationary and the field is rotated.

This construction has distinct advantages. A rotating armature requires slip rings for carrying current to the external load. Such rings are difficult to insulate and are a frequent source of trouble, often causing opens and short circuits. A stationary armature requires no slip rings. The armature leads can be continuously insulated conductors from the armature

coils to the bus bars. Also, it is more difficult to insulate the conductors in a rotating armature than in a stationary armature, because of the centrifugal force resulting from rotation. The stationary armature makes it possible to operate alternators at voltages that are impossible in d.c. generators.

The slip rings for the rotating field offer no serious difficulty. The field voltage seldom exceeds 250 volts and the amount of power is small compared to the power delivered by the armature.

SINGLE PHASE ALTERNATOR

If an alternator is wound to deliver only one voltage to an external load, it is a SINGLE PHASE ALTERNATOR. If the armature coils on a d.c. armature were connected to two slip rings instead of a commutator, it would be a single phase alternator. The armature has a single phase winding. Actually, very few alternator armatures are wound this way, but the general principles in winding the armature of an alternator are the same as in d.c. windings. The types of winding used in alternators and the winding methods will be discussed later.

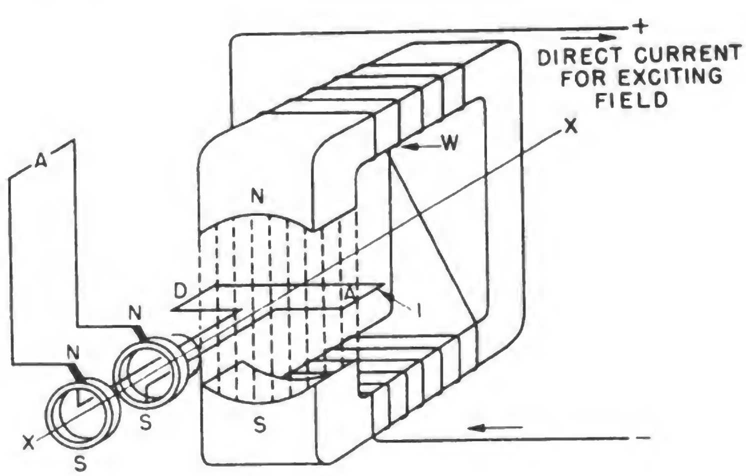


Figure 139.—Single phase alternator.

Figure 139 is a simple representation of a single phase, two pole alternator. When the coil is rotated in the flux field, an alternating emf is induced in the coil. If the terminals of this coil are brought out to two slip rings as shown, an alternating

current can be delivered to an external load. This current will have a sine wave form as shown in figure 140. All alternators are designed to produce as nearly as possible a voltage which has a pure sine wave, because that is the only type of voltage that will retain its shape when passed through a transformer.

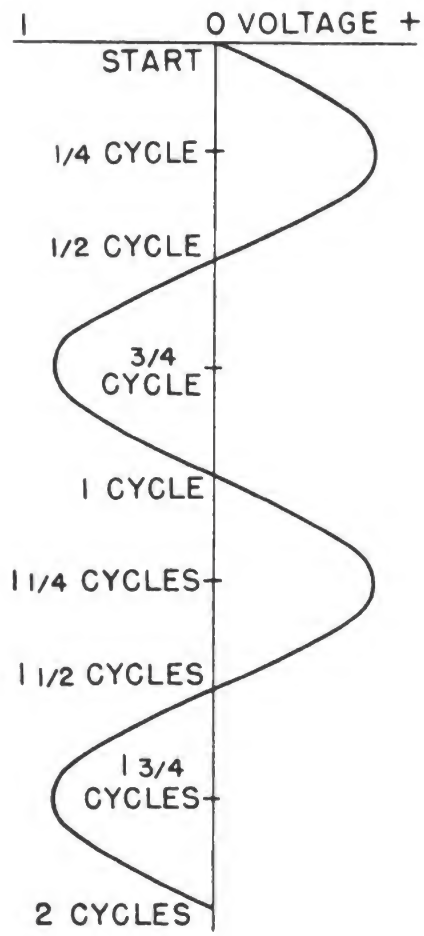


Figure 140.—Single phase a.c.

Single phase alternators are seldom used. Instead, POLYPHASE ALTERNATORS are used. A single phase alternator delivers only 57.7 percent of the power which it would deliver if it were wound three phase.

POLYPHASE WINDINGS

An alternator with two or more single phase windings symmetrically spaced on its armature has a polyphase winding. It

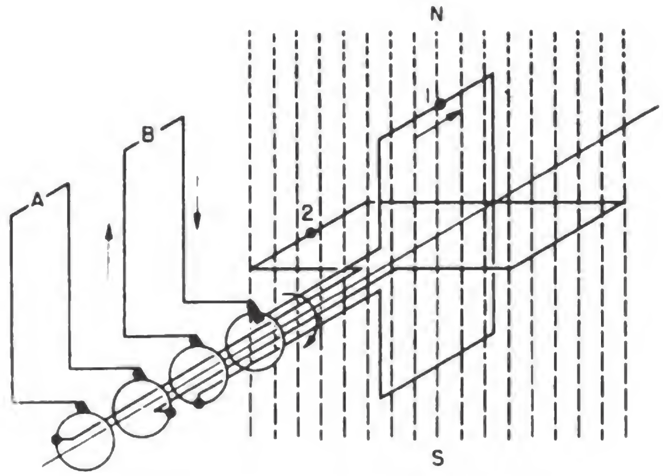


Figure 141.—Two phase alternator.

will generate polyphase voltages. Figure 141 is a simple diagram of an alternator which has two single phase windings 90° apart.

Two voltages are generated in the alternator. The two voltages are alike in every respect, but there is a time displacement of 90° between them. As shown in figure 142, voltage E

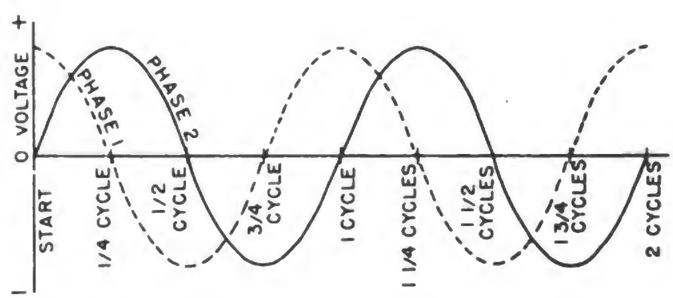


Figure 142.—Two phase a.c.

reaches its maximum value 90° behind voltage E. This is a two phase alternator. If the ends of the two windings are brought out to four slip rings, a two phase voltage can be delivered to an external load.

If the armature of the alternator has three single phase windings symmetrically placed around its armature, three voltages can be generated. These windings would be 120° apart. Therefore, the time displacement of the voltages would be 120°.

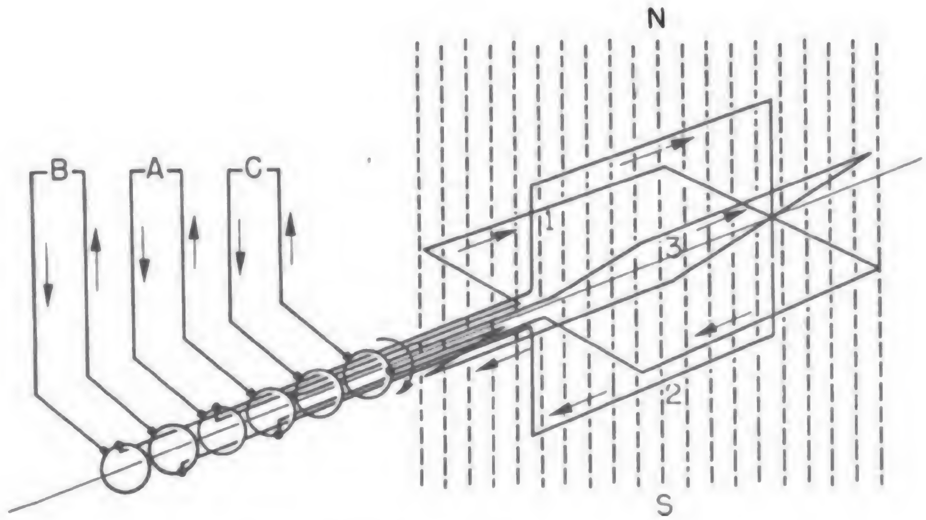


Figure 143.—Three phase alternator.

An elementary diagram of a three phase alternator is shown in figure 143. The sine waves for the voltages generated in this alternator are shown in figure 144.

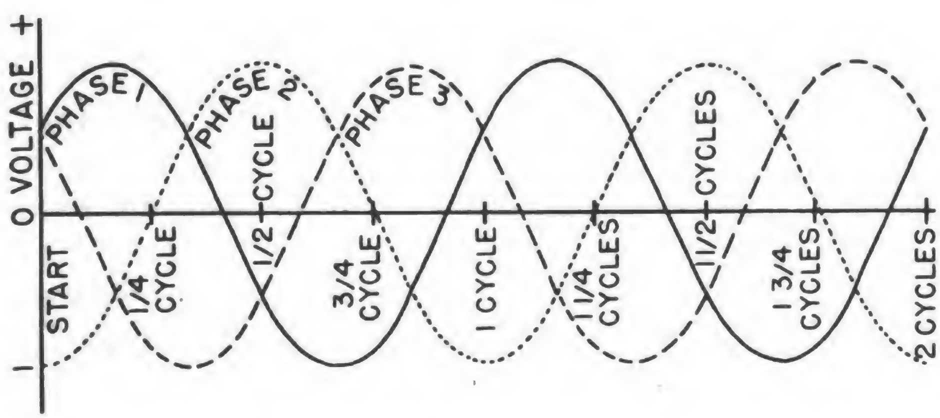


Figure 144.—Three phase a.c.

A three phase alternator is generally used because it gives a smooth power, it is smaller than a single phase alternator of the same power rating, there is less pulsating armature reaction, and the system requires less copper than a single phase system which delivers the same power.

STAR AND DELTA CONNECTIONS

The diagram in figure 143 shows the six terminals of a three phase winding brought out to six slip rings. BUT THIS METHOD

ISN'T USED. Instead, the windings are connected either STAR or DELTA, and only three leads are brought out. In the rotating armature type of alternator, these three leads are connected to three slip rings. In the stationary armature type, the three leads are connected directly to the bus bars.

The STAR connection is also known as a *Y* connection because the schematic diagram of this connection resembles the letter *Y*.

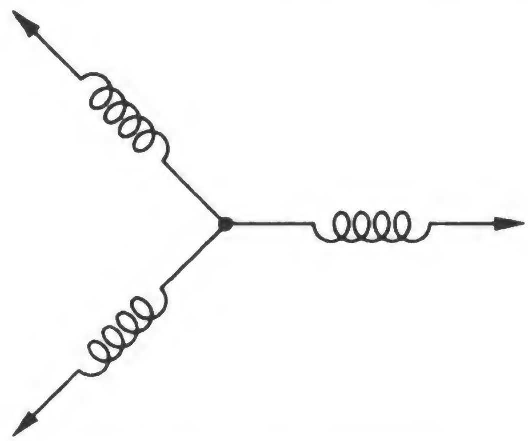


Figure 145.—A star connection.

In the star connection, either all the start or all the finish ends of the three windings are connected together as shown in the schematic diagram in figure 145. The three remaining ends are brought out to the external load.

The voltages generated in the three windings are represented vectorially in figure 146 for both types of connections. In the

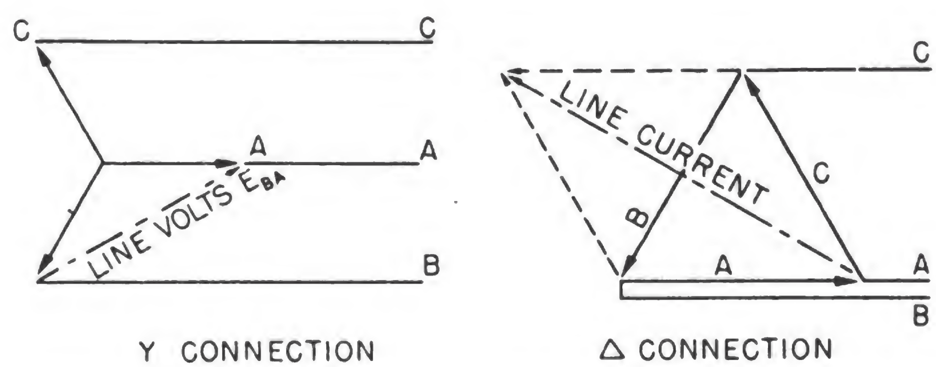


Figure 146.—Vector diagram of voltages in three phase circuits.

STAR connection, the voltage between any two of the lines is equal to the voltage generated in one coil multiplied by 1.73.

This means that if the voltage generated in one of the phase windings is 100 volts, the voltage across any two lines is 173 volts. In the star connection, the windings are in series with the line, so the line current must be the same as the phase current.

The DELTA connection is so named because it resembles the Greek letter Δ. To make the delta connection, the finish end of the first winding is connected to the start of the second winding, the finish of the second winding is connected to the start of the third winding, and the finish of the third winding is connected to the start of the first winding. A schematic diagram of the delta connection is shown in figure 147. At first it may appear that a high current would flow continuously through

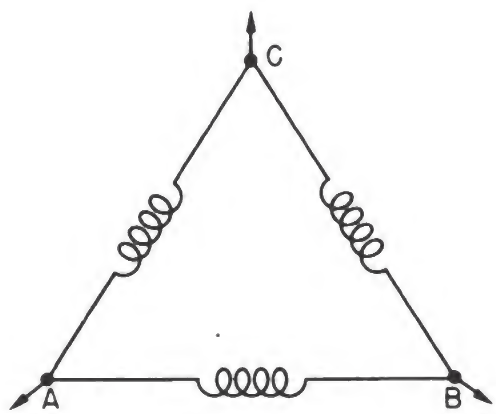


Figure 147.—A delta connection.

the windings. But because of the phase displacement of the three generated voltages, negligible currents or no current will flow if the alternator is properly designed and constructed.

The line leads are taken from points *A*, *B*, and *C*. The voltage between any two of the lines is equal to the PHASE VOLTAGE, that is, the VOLTAGE GENERATED IN ONE WINDING. However, the line current is 1.73 times the current in any one phase of the winding.

An explanation of the current and voltage relationships between phase and line in three phase alternators will be given in a later discussion of polyphase circuits.

POWER IN A THREE-PHASE, BALANCED, Y-CONNECTED LOAD

The total power of a three-phase system will be the sum of the powers in each individual phase. In the BALANCED three-phase system this amounts to three times the power in one of the phases, since each phase would have the same power expenditure —

Total power $= 3 \times$ phase power

$$P_t = 3\ (ei \cos \theta)$$

In the Y-connected system—

$$e = E/\ 1.73,$$

$$i = I,$$

$$\text{and, } 3 = 1.73 \times 1.73$$

$$\text{Therefore, } P_t = 1.73 \times 1.73 \times E/\ 1.73 \times I \times \cos \theta$$

$$= 1.73\ EI \cos \theta$$

Cos θ is the power factor of the load or the cosine of the "phase angle"—that angle between the phase·voltage and the phase current.

POWER IN A THREE-PHASE, BALANCED, DELTA-CONNECTED LOAD

IN ANY POLYPHASE SYSTEM, THE TOTAL POWER WILL BE THE SUM OF THE PHASE POWERS, and in any balanced system, the power in all phases must be equal. In the BALANCED delta-connected load, therefore—

$$P_t = 3\ ei \cos \theta$$

$$\text{But since } e = E$$

$$\text{and } i = I/\ 1.73$$

$$\text{therefore } P_t = 1.73 \times 1.73 \times E \times I/1.73 \times \cos \theta$$

$$= 1.73\ EI \cos \theta$$

This equation is obviously the same as the equation for total power of a balanced, Y-connected load and we conclude that this equation represents the expression of total power in ANY BALANCED, THREE-PHASE SYSTEM.

RATING ALTERNATORS

You know that the power of an a.c. circuit depends upon the power factor of the circuit, as well as on the current and volt-

age. When the power factor is low, and an alternator is delivering a load well within its rated capacity, the current may be far in excess of the rated capacity of the alternator.

There is a limit to the amount of current which an alternator can carry because of the heating of the conductors. Therefore, the rating of an alternator cannot be expressed in kilowatts as in a d.c. generator. It must be expressed in some unit that will take into account the TOTAL CURRENT DELIVERED by the alternator. To do this, the capacity is expressed in kv. amps., or KILOVOLT AMPERES. In this way the machine's capacity is independent of the power factor of the system it is supplying.

Sometimes the power factor of the system which the alternator supplies is kept constant. The alternator for the main propulsion motor on some destroyer escorts is an example. In a case of this kind, the alternator rating is often given in kw. at the given power factor.

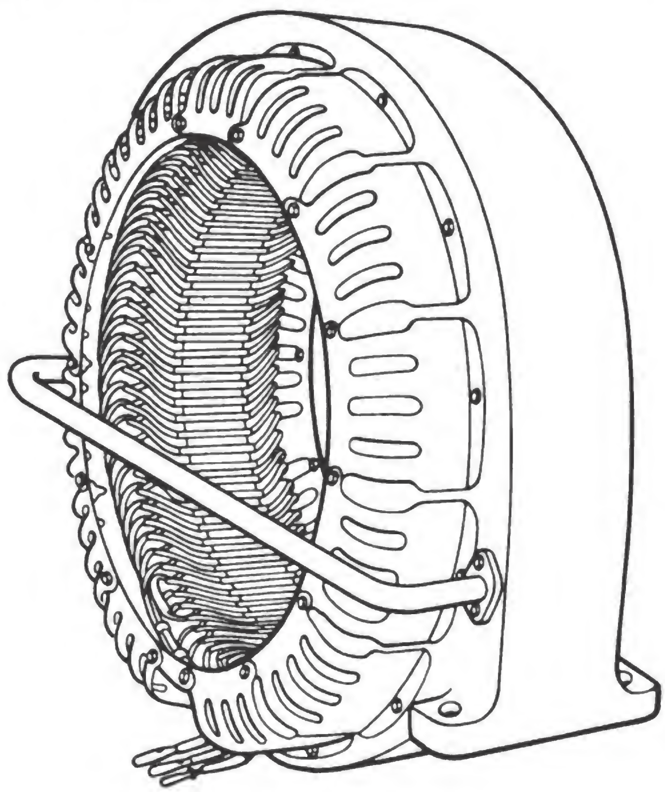


Figure 148.—An alternator stator.

ALTERNATOR CONSTRUCTION

As has been stated, most alternators have a rotating field and stationary armature. The STATIONARY PART of the armature

is called the STATOR. The stator consists of a laminated iron core and the armature windings. The windings are embedded in slots in the core as shown in figure 148, and the core is secured to the stator frame.

The ROTATING part of the alternator is called the ROTOR. When the field of the alternator is placed upon the rotor, it is either

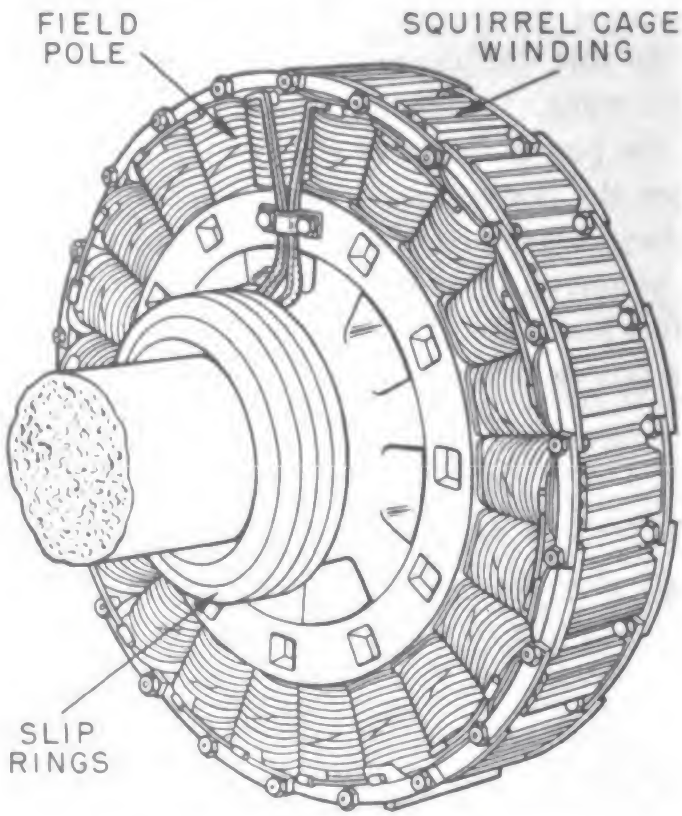


Figure 149.—Salient pole type rotor.

the SALIENT POLE TYPE or the TURBO TYPE. In either case, the alternator is separately excited by a d.c. generator. The d.c. generator may be driven by the same shaft that drives the rotor of the alternator or by a separate prime mover.

The SALIENT POLE TYPE rotor is shown in figure 149. A number of separately wound poles of the type shown in figure 150 are dovetailed or bolted to the spider of the rotor. The field windings are then all connected in series, or groups of coils are connected in series and the groups connected in parallel, and the ends of the circuits connected to slip rings. The slip rings are insulated from and mounted on the rotor shaft.

Copper bars are often embedded in the face of the field pole and connected at their ends with brass rings. These are used in engine driven alternators to improve parallel operation.

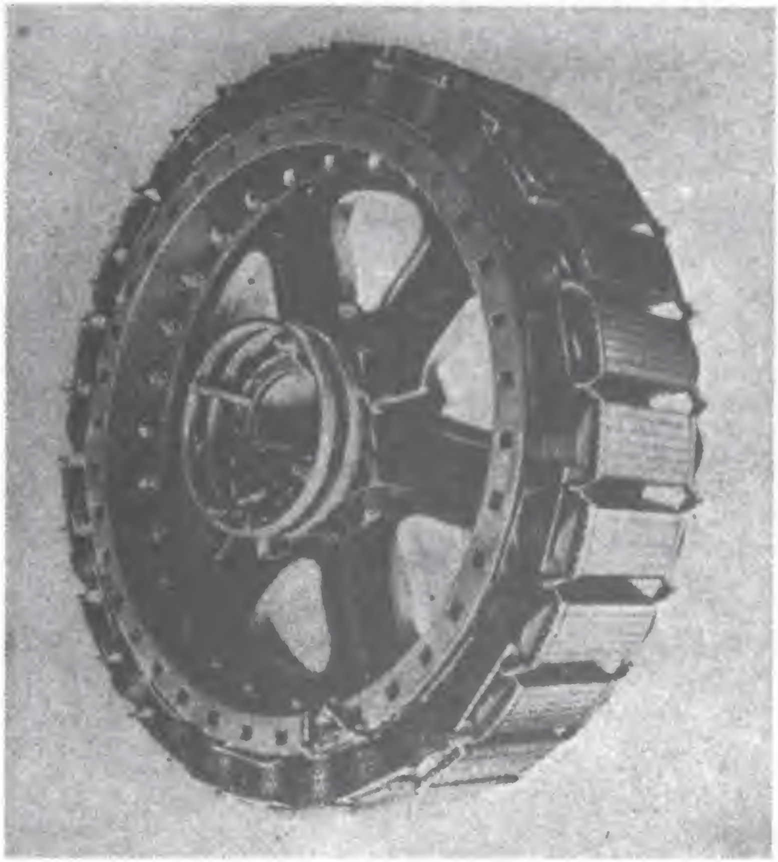


Figure 150.—Separately wound pole rotor.

The salient pole rotor is used in slower speed alternators which are driven by engines, water power, geared turbines, and electric motors.

In higher speed alternators driven by direct-connected steam turbines, the TURBO TYPE rotor is more practical. It is difficult to build projecting poles which will withstand the centrifugal force at high speeds. The projecting poles also cause excessive wind losses and are noisy.

The turbo type rotor is cylindrical, small in diameter, and it has its winding embedded in slots in its face (figure 151). These windings are so arranged that they form distinct poles, usually two or four. Figure 152 will give you an idea of how these windings are in the face of the rotor.

Naturally, with its small diameter this rotor would have to be longer to provide sufficient field strength. The turbo con-

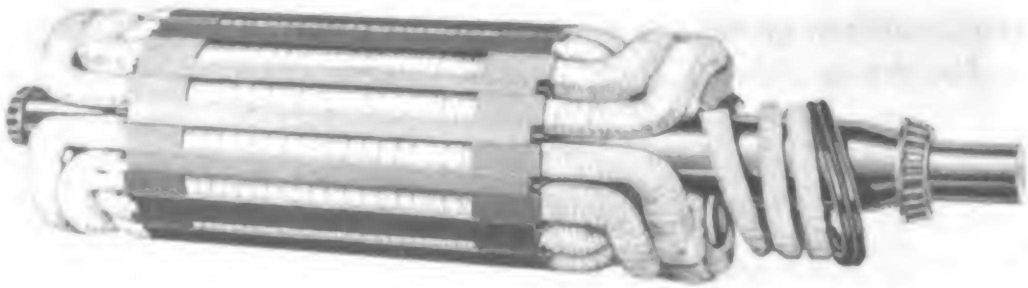


Figure 151.—A turbo wound rotor.

struction results in considerable heat being liberated in small spaces; it is necessary to use forced ventilation. The alternator is enclosed so that the air currents can be directed and noise reduced.

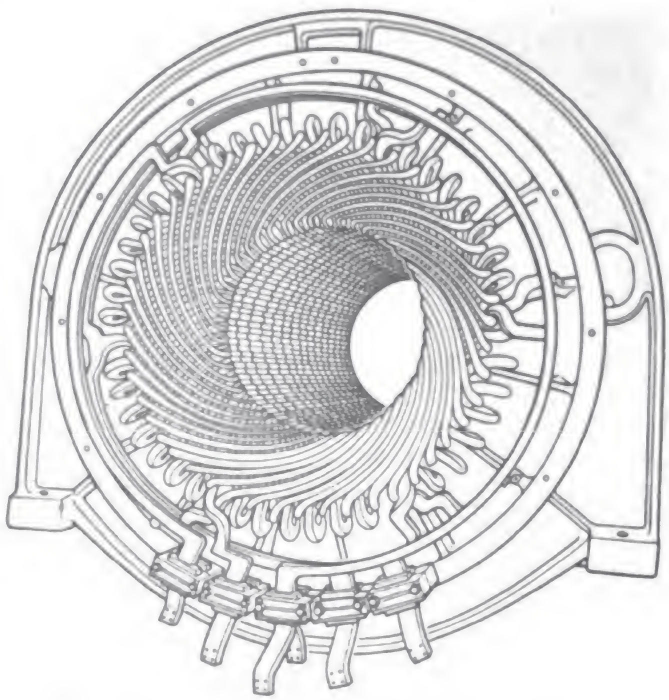


Figure 152.—A turbo wound stator.

For practical reasons, all direct-connected turbine driven alternators of 500 kv. amp. and greater will be of turbo construction. However, for sizes smaller than 500 kv. amp., it is more economical to use salient pole alternators driven at slower speed. If necessary, reduction gears are used to reduce the speed.

VOLTAGE REGULATION

As the LOAD on a shunt generator is INCREASED, the TERMINAL VOLTAGE DROPS. This voltage drop is caused by armature reaction, by IR drop in the armature, and by the weakened field which results from the first two causes. The alternator, on the other hand, is affected by the first two, but not by the weakened field. However, in addition to the IR drop in the armature, there is a reactance drop IX.

In the d.c. generator, ARMATURE REACTION depends upon the current flowing and on the position of the brushes. In an alternator, it depends upon the STATOR CURRENT and on the POWER FACTOR of the circuit.

A stator current which lags the voltage by 90° has an effect similar to moving the brushes forward 90° in a d.c. generator. This is shown back in figure 52. The stator current does not reach its maximum until the south pole has advanced 90 electrical degrees. All the flux produced by the stator opposes the field flux, and therefore weakens it. This causes the generated emf to go down.

If the current leads the voltage by 90°, it reaches its maximum value 90° electrical degrees before the south pole moves under the stator conductors. The flux of the stator conductors is now in the same direction as the field flux and strengthens it. This causes an increase in the generated emf.

Thus you may conclude that the terminal voltage varies with the IR and IX drops in the stator winding and the power factor of the load. An alternator which has satisfactory voltage regulation at unity power factor may have very poor regulation at low power factor.

The regulation of alternators is inherently poorer than the regulation of d.c. generators. In addition to this, the starting current of an a.c. induction motor may be eight times its normal full load current. This current may last for only a few cycles, and it is of low power factor. But, unless it is carefully considered in the design of the plant, it will tend to reduce the voltage of the system to the point where all controller holding coils. bus transfers, and so on, connected to the system will

drop out. Close voltage regulation and control is necessary to obtain satisfactory operation of all electrical equipment on the system.

COMPENSATING FOR VOLTAGE REGULATION

The alternator field current is supplied by a stabilized shunt generator called the EXCITER. The voltage regulation caused by the varying load on the alternator must be compensated for by controlling the current which this exciter supplies to the rotating field.

While the alternator is delivering normal load, the EXCITER furnishes a STEADY CURRENT to the alternator field. If the a.c. load suddenly increases, it results in a decrease in terminal voltage of the alternator. In order to counteract this decrease in voltage it is necessary to increase the d.c. current supplied to the field of the alternator. Thus, you see, it is necessary to change the excitation of the alternator each time the load changes in order to maintain a constant voltage.

For conditions which exist on the electrical system aboard ship, hand adjustment of the alternator field is neither quick enough nor accurate enough to maintain a constant voltage. So, AUTOMATIC VOLTAGE REGULATORS are used.

HOW IT IS DONE

For the EMERGENCY GENERATOR, where the high degree of regulation required by ship's service plant is not essential, the VARIABLE RESISTOR type regulator is used. It has a voltage-sensitive element in the form of a solenoid or torque motor. This element is actuated by the a.c. voltage. Any change in the a.c. voltage will cause the sensitive element to exert a mechanical force on a variable resistor in the alternator or in the exciter field. The regulator is normally at rest and operates only when a change in excitation is required.

The RHEOSTAT generally consists of resistance plates stacked one over the other, which are tilted together or apart by the mechanical action of the voltage-sensitive element, thus increasing or decreasing the resistance. All the resistance may be in-

serted or removed within a few cycles or it may be varied slowly.

The variable resistor regulator, also called DIRECT ACTING RHEOSTATIC REGULATOR, is usually placed in the field circuit of the d.c. exciter, except in the case of low capacity alternators.

INDIRECT ACTING, RHEOSTATIC TYPE ALTERNATOR

The indirect acting, rheostatic type of regulator is shown in figure 153. It provides for more accurate voltage regulation and is used on the ship's service alternators. It operates in the field of the alternator.

The voltage sensitive element, in this case a torque motor, is energized by a voltage directly proportional to the average

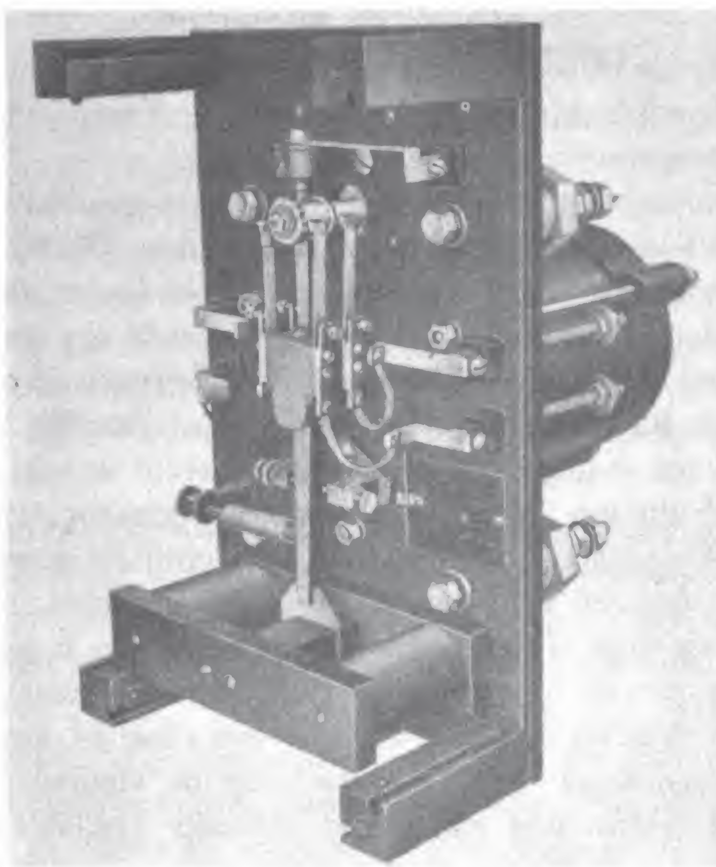


Figure 153.—Indirect acting, rheostatic type regulator.

voltage of the three-phase line. It controls a motor which operates the field rheostat, and it also controls relays which cut large blocks of resistance into or out of the field circuit.

The d.c. motor which operates the rheostat is controlled by the voltage sensitive elements. If the voltage decreases, the torque motor—voltage sensitive element—operates a set of relays which cause the rheostat motor to cut resistance out of the alternator field circuit until the voltage is normal again. If the voltage increases, the torque motor operates relays which cause the rheostat motor to run in the opposite direction and to cut resistance into the circuit.

The response of the MOTOR-OPERATED RHEOSTAT is too slow to handle large, sudden changes in voltage. When these occur, the VOLTAGE SENSITIVE element actuates high speed relays which insert or cut out large blocks of resistance in a vibrating manner until the motor operated rheostat has time to make the final adjustment.

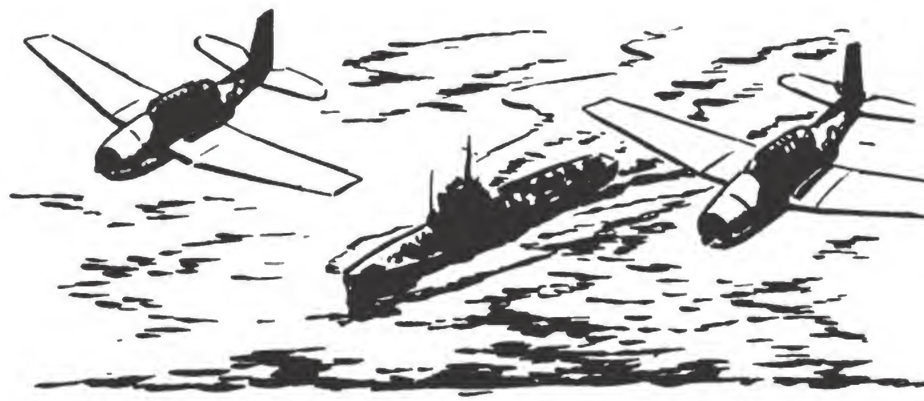
EQUALIZING REACTOR

The purpose of the EQUALIZING REACTOR is to prevent one alternator from furnishing all the reactive kv. amp. when alternators are operating in parallel.

The reactor supplies a voltage which is in quadrature to the line current to one phase of the torque motor. Now, if all the alternators are operating at the same power factor, those voltages due to load current are in approximately the same phase relation and affect all regulators alike. However, if one alternator tends to carry more than its share of reactive kv. amp., the additional voltage due to the line current swings more in phase with the a.c. line voltage, and the regulator responds to reduce the excitation on this alternator until its power factor has been equalized with that of the other machines.

This discussion of automatic voltage regulators is not for the purpose of describing any one of the various regulators in detail. The detailed construction and operation of any voltage regulator approved for Navy use may be studied from the equipment, plans, and instruction manuals available on each vessel.

A manually-operated rheostat is installed to control the voltage in case the automatic regulator should fail, or in instances where manual control is desired. A switch is provided by which the control may be shifted from the automatic regulators to the manually operated rheostat.



CHAPTER 18

PARALLEL OPERATION OF ALTERNATORS

WATCH YOUR CONNECTIONS

Alternators on board ship must be capable of operating in parallel. They are operated in parallel for the same reason d.c. generators are operated in parallel—to increase the plant capacity beyond the range of a single alternator—to make it possible to shut down an alternator and bring a standby machine on the line without interrupting the supply—and to serve as additional reserve power for expected demands. However, the parallel operation differs somewhat from the parallel operation of d.c. generators.

Alternators, like a.c. generators, must also have equal voltages and correct polarity. And in addition they must have the same frequency, the same phase rotation, and must be parallel at an instant when their voltage sine waves have equal instantaneous value.

In the case of d.c. generators, the voltage of the alternator and the polarity can be checked with a voltmeter. The voltage of the alternator can also be checked with a voltmeter, but SPECIAL SYNCHRONIZING instruments must be used to check the other conditions.

The CORRECT PHASE ROTATION is obtained by connecting corresponding phase leads of the alternators to the same buses. This is checked when the alternators are installed. If an alter-

nator is temporarily disconnected, the phases should be plainly and accurately marked, so that they can be connected back in exactly the same way.

The polarity of the alternators is changing regularly—120 times per second on a 60 cycle line. You can see that at any instant the polarity of the incoming alternator may or may not be the same as the operating alternator. Their polarities—direction of generated voltage—must be the SAME at the INSTANT the machines are PARALLELED.

If the direction of current in the incoming alternator and the operating alternator are both toward the line at the time the incoming switch is closed, the polarity is correct for paralleling. But suppose the incoming alternator has a voltage OPPOSITE in direction to the voltage of the operating machine. That is the same thing as trying to parallel two d.c. generators of opposite polarity. The incoming alternator becomes essentially a SHORT CIRCUIT on the operating machine.

If the switch of the incoming machine is closed somewhere between the extreme conditions, a portion of the current of the operating machine will be diverted to the incoming machine, tending to drive it as a motor. To avoid these conditions, synchronizing instruments are used to indicate to the operator the proper instant to close the switch of the incoming machine.

SYNCHRONIZING LAMPS

One of the oldest methods of synchronizing alternators is by use of lamps. Figure 154 shows how the lamps are connected. Three incandescent lamps are connected around the terminals of the switch to the incoming alternator. You will notice one side of each lamp is connected to a bus bar energized by the operating alternator. The other side of the lamp is connected to one phase of the incoming alternator.

When the main switch is open, these lamps are energized by a voltage which depends upon the phase relation and relative magnitude of the incoming alternator voltage and the bus voltage. If the voltage of the incoming alternator and the operating alternator are EQUAL and in the SAME direction—both toward

the buses—the LAMPS WILL BE DARK. That is the PROPER INSTANT to close the switch of the incoming alternator.

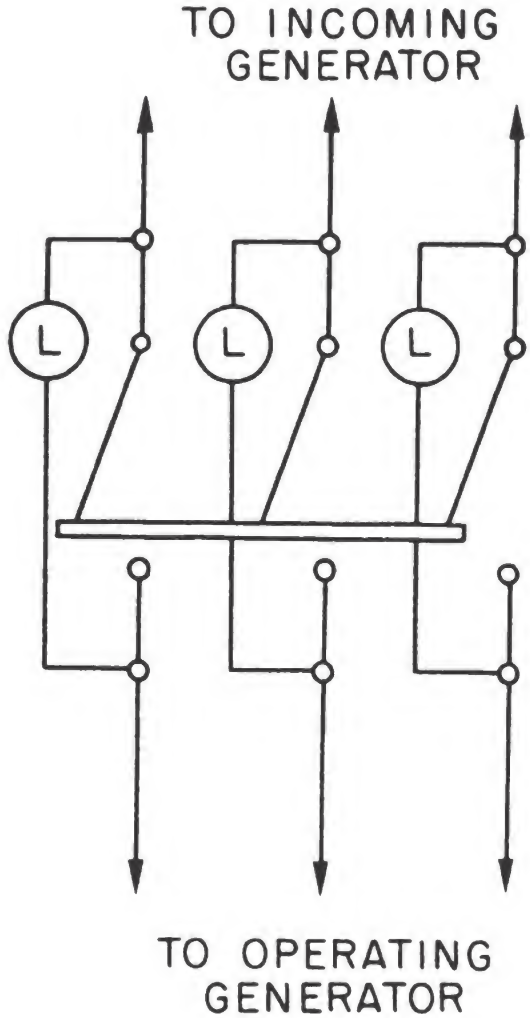


Figure 154.—Circuit for using synchronizing lamps.

However, if the generators are out of phase with each other, the voltage of the operating generator will be toward the bus bar when the voltage of the incoming generator is in the opposite direction. The voltage across the terminals of the lamps will be the SUM of the voltages of the two machines. The lamps will be brilliantly lighted when the two machines are EXACTLY OUT of PHASE and that is the WORST POSSIBLE condition for paralleling.

If the two machines are operating at DIFFERENT FREQUENCIES, the resultant voltage across the lamps will change continuously

and the LAMPS WILL FLICKER. The rate of flicker will depend upon the difference in frequencies of the two machines. If the FREQUENCIES of the two machines are WIDELY SEPARATED, the lights will GROW BRIGHT and BECOME DARK in very rapid sequences. As the frequencies of the two machines become more equal, the flicker of the lights will slow down. When the flicker becomes very slow, the switch is closed while the lamps are dark. At this instant the simultaneous voltages of the two alternators are equal and in the same direction—same polarity.

This method is used to synchronize alternators with RELATIVELY SLOW SPEEDS, but it is not sufficiently sensitive for high speed turbo units. There may be a CONSIDERABLE PHASE DIFFERENCE at the INSTANT the LAMPS ARE DARK.

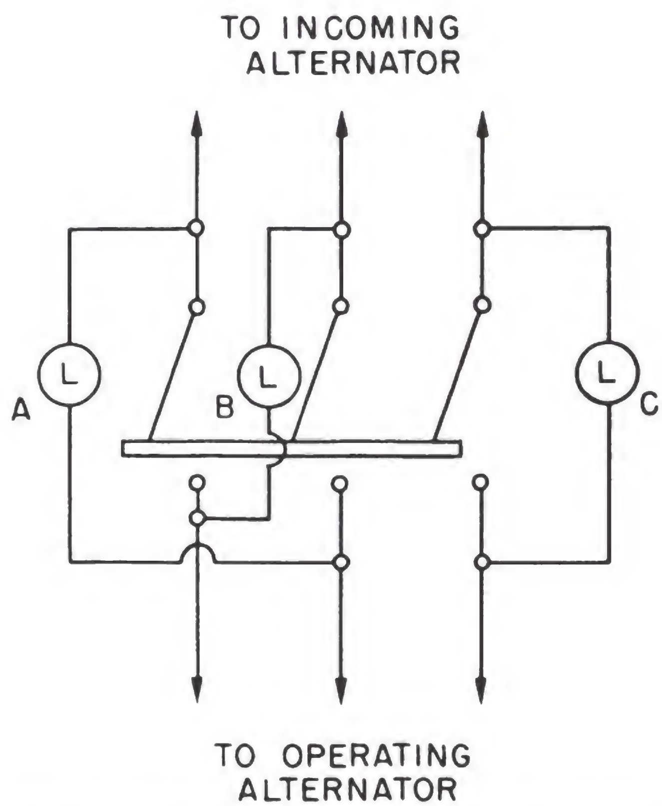


Figure 155.—Synchro lamps, "two bright and one dark" method.

This objection may be overcome by what is called the "two bright and one dark" method. Connections for this method are shown in figure 155. It will be observed that the connections of the lamps in two of the phases are crossed. With this connection, the alternators are in synchronism when lamps *A* and

B are at maximum bright and C is dark. When the alternators are APPROACHING SYNCHRONISM, one of the bright lamps is GROWING BRIGHTER and the other one is DECREASING in BRILLIANCY. It is the distinction between the two bright lamps which permits the operator to determine more accurately the point at which the switch should be closed.

SYNCHROSCOPE

• The SYNCHROSCOPE is used to obtain accurately the position for synchronizing alternators. The synchroscope is based on the principle of the power factor indicator. In figure 156 the

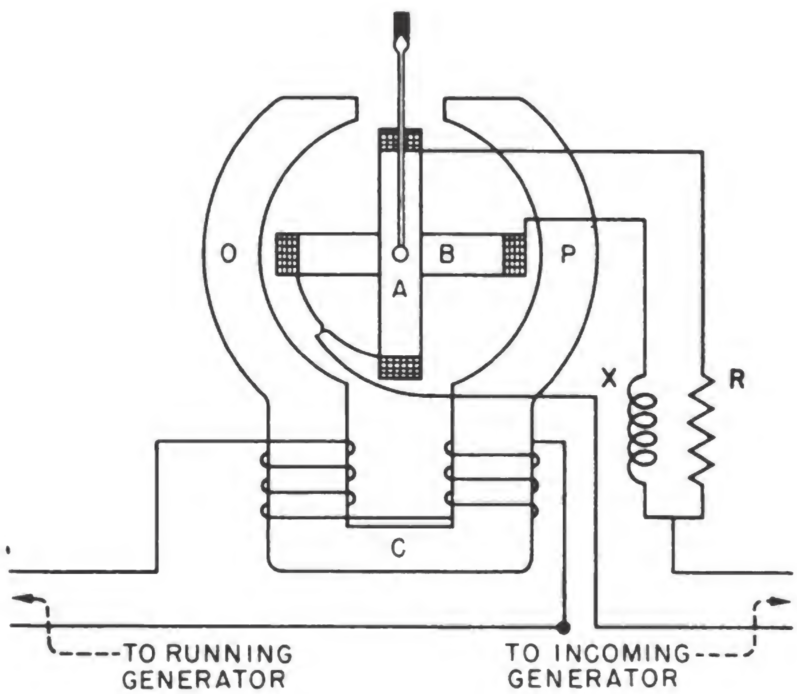


Figure 156.—Synchroscope circuit and dial.

magnet *C* of the instrument is excited by a winding which is connected through a potential transformer to the incoming alternator. Two moving coils *A* and *B* are placed at an angle of 90° from each other. The connections are made through slip rings attached to the ends of these coils and to a common point between the coils. The moving element, which consists of the two coils, is connected through a potential transformer across

the bus bars. One coil is connected to one of the bus bars through a resistance R. The other coil is connected to the same bus bar through a reactance X. The common connection is connected to another bus bar.

If the frequency of the incoming machine is the same as the bus, the combined effect of the magnetic field of the magnet and the magnetic field of the moving coils keeps the moving element in a STATIONARY POSITION. However, if the incoming machine is too fast, the moving element will rotate in one direction. If the incoming machine is running too slow, the moving element will rotate in the opposite direction. If there is a great difference in the frequencies of the two alternators, the moving element will actually rotate at a speed which is dependent upon the difference in frequencies.

As the machines approach the same frequencies, the indicator attached to the moving element of the synchroscope will slow down.

The switch to the incoming machine should be closed when the indicator is MOVING SLOWLY IN THE FAST DIRECTION and JUST BEFORE it reaches the point of exact synchronism.

Both the synchroscope and synchronizing lamps are usually installed and used for paralleling alternators.

This is the story of paralleling an alternator with an energized bus—be sure you understand it.

DIVIDING THE LOAD

Once the alternators have been paralleled, the next step is to divide the load between them, or in some instances, shift all the load from the operating alternator to the alternator just brought on the line.

This shifting of load from one alternator to another is accomplished by a method altogether different from that used with d.c. generators. In the case of d.c. generators, the load or a part of the load is shifted from one machine to the other by operation of the field rheostat. That method doesn't work on alternators.

If two alternators are operating in parallel and the field excitation of one is increased as the field excitation of the other

one is decreased, the load division will not be appreciably changed, because a REACTIVE CURRENT will circulate between the two machines. This reactive current does not affect the kilowatt output of the alternators. However, it does increase the IR loss in the armature windings. This causes excessive heating and cuts down the efficiency of the alternators.

AN ALTERNATOR IS CAUSED TO TAKE MORE LOAD BY INCREASING THE POWER OF ITS PRIME MOVER. This is done by adjusting the governor or throttle of the prime mover.

INCREASING the POWER of the prime mover of an alternator naturally tends to INCREASE the SPEED of the alternator above the synchronous speed for the system. An increase in speed would pull the parallel alternators out of synchronism. But once alternators are operating in parallel they have a tendency to remain in step. So, instead of the speed of the alternators increasing, the ALTERNATOR TAKES MORE of the LOAD.

You may ask why two alternators operating in parallel tend to remain in step. Well, if one alternator attempts to pull out of step, a current is developed which circulates between the two machines. This current tends to accelerate the lagging machine and to retard the leading machine and so acts to keep the two alternators in synchronism.

PARALLELING AN ALTERNATOR WITH AN ENERGIZED BUS

Now you have the overall picture of parallel operation, and it's time to sum up the steps in paralleling. Here's the situation—one alternator is operating and the other is shut down. Your problem is to start the second alternator, parallel it with the first, and then divide the load between the two alternators. This is the procedure to follow—

FIRST, MAKE A ROUTINE INSPECTION OF THE EQUIPMENT—

- See that the alternator circuit breaker and field switch are open.
- Be sure that the alternator disconnect link is closed.
- Cut full resistance into the alternator field and d.c. generator field. Turn the voltage regulator transfer switch to the OFF position.

SECOND, START AND ADJUST THE SECOND ALTERNATOR BY THE FOLLOWING STEPS—

Start the prime mover and bring it up to normal speed.

Decrease the resistance in the d.c. generator field until the exciter voltage is correct.

Close the alternator field switch.

Adjust the manually operated field rheostat until the alternator voltage equals the voltage of the line. This adjustment should be made as accurately as possible.

Check the exciter voltage. Make the adjustment necessary to bring it to normal.

Cut in the voltage regulator by turning the regulator transfer switch to NORMAL. If necessary, use the rheostat to correct the voltage setting.

Check the frequency with the frequency meter. Use the governor motor control switch to adjust the prime mover's speed to correct any errors in frequency.

Check the alternator voltage again to see that it is equal to the bus voltage.

THIRD, PARALLEL THE TWO ALTERNATORS BY THE FOLLOWING STEPS—

Put the synchronizing switch in the ON position.

Adjust the speed of the incoming alternator until the synchroscope rotates very slowly in the fast direction.

Be sure that the voltage of the incoming alternator remains equal to the bus voltage.

Close the alternator circuit breaker just before the synchroscope pointer passes through zero position—and now the two alternators are operating in parallel.

FOURTH, SHIFT PART OF THE LOAD TO THE INCOMING ALTERNATOR. Here are the steps—

Increase the power to the prime mover of the incoming alternator while you decrease the power to the prime mover of the other alternator. The power of the prime mover is increased by turning the governor motor control switch toward RAISE and decreased by turning the switch toward LOWER.

Check the load shift by reading the wattmeters.

When the load is properly divided between the two alternators, check the ammeters and power factor meters for further indication of proper operation.

Adjust the exciter voltage of the alternator field until the power factor meters read the same.

If no power factor meters are available adjust the excitation voltage until the ammeters read the lowest total value.

POWER FACTOR METER

The principle of construction of the power factor meter is shown in figure 157. The meter contains fixed coils *A* and *B*, which carry the circuit current. Coils *C* and *D* are fastened rigidly together and mounted on a spindle that is free to rotate. There is no mechanical control, such as a spring, for this moving element. The angle between the coils is 90°, or nearly 90°. Coils *C* and *D* are connected together at the common point *E*, and *E* is connected to the same side of the circuit as coils *A* and *B*. A noninductive resistance *R* is connected be-

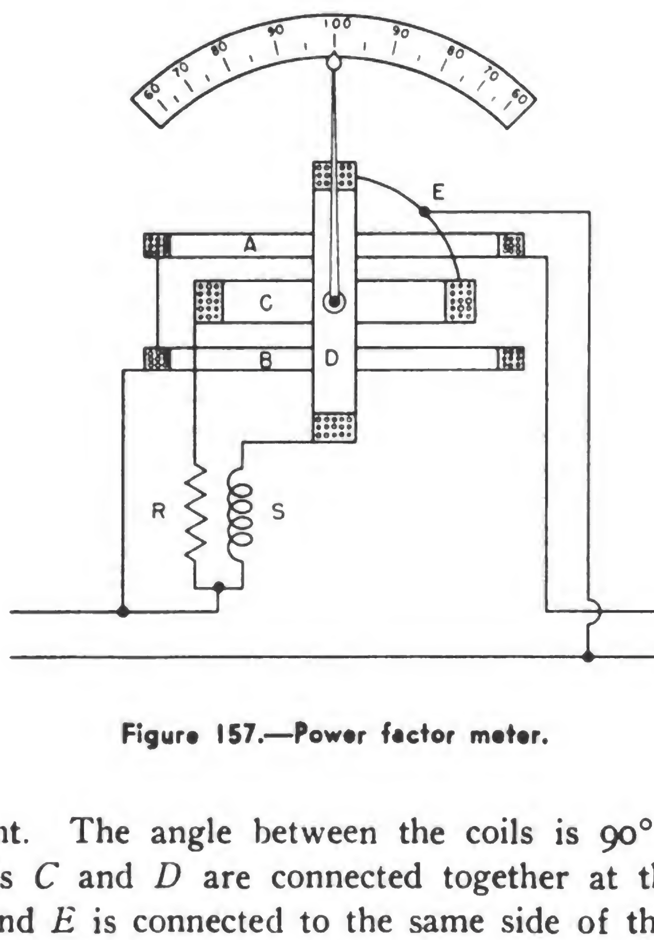


Figure 157.—Power factor meter.

tween coil *C* and the side of the line opposite *E*. A high inductance *L* is connected between the same line and coil *D*.

Assume for the moment that *L* is PURE INDUCTANCE and *R* is PURE RESISTANCE—then the currents in coils *C* and *D* are 90° out of phase.

Now suppose the power factor of the circuit is unity. The current in coil *D* is lagging the line current by 90°. So, the flux around coil *D* lags the flux of coils *A* and *B,* and NO DEFINITE TORQUE IS DEVELOPED.

But current in coil *C* IS IN PHASE WITH THE LINE CURRENT. Therefore, the flux of coil *C* is in phase with the flux of coils *A* and *B* and the resulting torque will move the plane of coil *C* to the plane of coils *A* and *B*.

Hence, at unity power factor, the moving element takes such a position that coil *C* is in the plane of coils *A* and *B*. The indicator is fixed to point to unity or 100 percent power factor.

If the power factor of the load is zero, the current through coils *A* and *B* is 90° out of phase with the voltage. That means it is in phase with the current through coil *D* and 90° out of phase with the current through coil *C*. Now the flux of coil *C* is 90° out of phase with the flux of coils *A* and *B* and it doesn't exert any definite torque. The flux of coil *D* is in phase with the flux of coils *A* and *B*. The flux of the three coils will tend to line up along the same axis. Thus a torque is exerted pulling coil *D* into the plane of coils *A* and *B*. The moving element is rotated to a position 90° from its position at unity power factor. So, when the current changes its TIME PHASE by 90°, the moving element changes its position by 90°. The direction in which the element turns depends on whether the current is leading or lagging.

If the current and voltage are out of phase by any angle less than 90°, the element will move a corresponding distance. The scale may be calibrated in degrees; the pointer will then indicate the power factor ANGLE of the circuit. If the scale is marked to indicate the COSINE of the angle of lead or lag, the power factor can be read directly from the scale.

It is impossible to obtain either pure resistance or pure inductance, so the current in coils *C* and *D* will not differ by exactly 90°. The space angle between coils *C* and *D* is made

equal to the phase difference between the currents of the two coils.

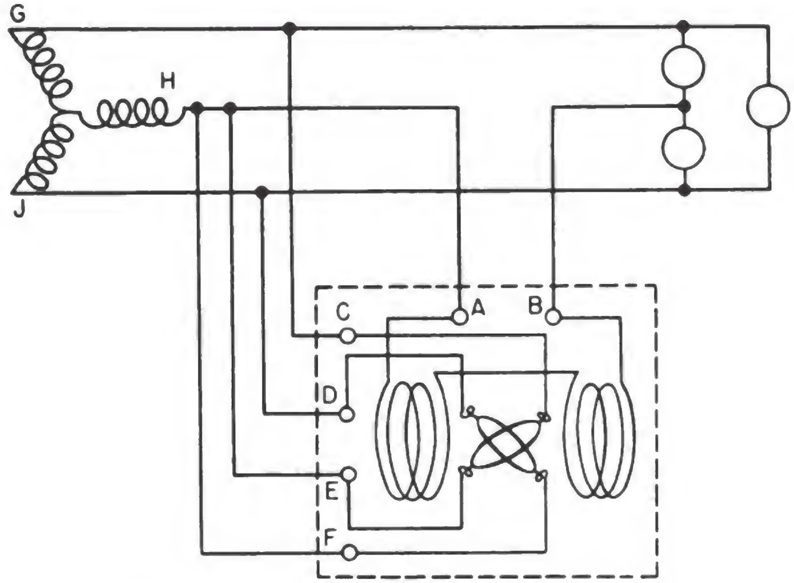


Figure 158.—Three-phase power factor meter.

If the angle between coils C and D is made to equal 120°, the meter can be used to determine the power factor of a three phase system, provided the load is a balanced load.

Figure 158 shows the connections for a three-phase power factor meter. The common connection is made to the same line as the stationary coil. One of the leads from the moving element is connected to one of the two remaining lines, and the other lead is connected to the third line of the system.

CARE OF ALTERNATORS

A.C. equipment should receive the same care as d.c. equipment and the same precautions must be observed. An alternator has no commutator, but the slip rings must be kept in good condition at all times. The brush tension should be kept at a pressure of four pounds per square inch of contact surface.

Of course the alternators must be kept at the CORRECT SPEED. Any variation in speed will cause a corresponding variation in the frequency of the line current. This would disturb the operation of all equipment on the line. Once adjusted, the speed is kept constant by governors on the prime mover.

DIESEL EMERGENCY GENERATOR

For emergency operation, DIESEL DRIVEN GENERATORS are installed. The typical plant consist of two such units, one forward and one aft. Each has appropriate switchboard and switching arrangements.

The capacity of the emergency unit varies according to the size of the vessel on which it is installed. But regardless of the size of the installation, the principle of operation is the same.

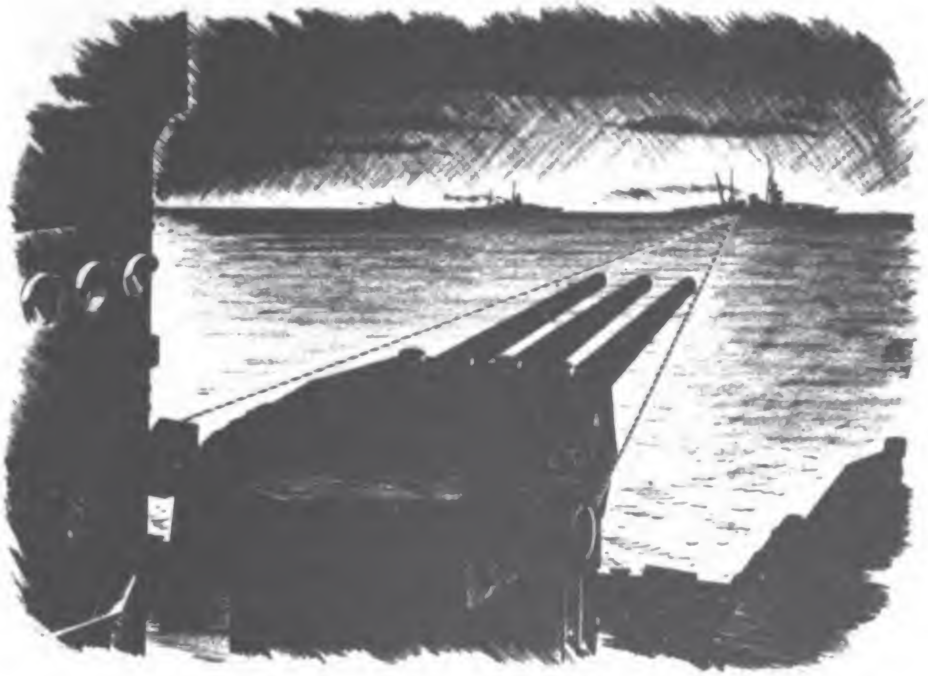
Diesel engines are started either by compressed air or by a small d.c. motor driven by storage batteries. The engines are designed to develop full rated load power within 10 seconds.

In a typical installation, the starting mechanism is actuated when the ship's supply voltage on the bus falls to 350 volts. The generators are not designed for parallel operation. So, when the ship's supply voltage fails, a transfer switch automatically throws the load from the main distribution switchboard to the emergency switchboard.

When the ship's supply voltage is restored and the voltage reaches a predetermined value—say 405 volts—the automatic transfer switch throws the load back to the main distribution switchboard. After this occurs, the engine must be stopped by hand and manually reset for automatic starting.

Since the generators are of limited capacity, only certain circuits can be supplied from the emergency bus. These include such circuits as the steering gear, boiler room auxiliaries, and the interior communication switchboard. If some vital circuit is secured, some non-vital but necessary circuit may be cut in, up to the capacity of the generator.

The emergency system is important. The wiring provisions differ for different ships. You should acquire a thorough knowledge of the emergency system aboard your ship.



CHAPTER 19

TRANSFORMERS

A REVIEW

The transformer is used primarily to STEP-UP or STEP-DOWN voltage in an a.c. circuit. You should remember that the RATIO of the secondary voltage to the primary voltage is the same as the ratio of the turns in the secondary winding to the turns in the primary winding, or—

$$\frac{E_s}{E_p} = \frac{T_s}{T_p}$$

So, if you wish to make a step-up transformer, you put more turns on the secondary than on the primary; and a step-down transformer has more turns on the primary.

The current flowing in the windings is determined by the load on the secondary. Neglecting iron and copper losses, the VOLT-AMPERE OUTPUT of the secondary is EQUAL to the VOLT-AMPERE INPUT to the primary, or $T_sE_s = I_pE_p$ Therefore—

$$\frac{I_s}{I_p} = \frac{E_p}{E_s}$$

and,

$$\frac{I_s}{I_p} = \frac{T_p}{T_s}$$

Or, another way of stating it—the power in the primary circuit is equal to the secondary power dissipation. You can't take more out than you put in.

COOLING TRANSFORMERS

All of the energy loss in a transformer is dissipated in the form of heat. This loss is small in proportion to the total capacity of the transformer. But, in transformers of larger capacity, it adds up to a considerable amount of heat. Thus, some method must be provided for cooling the transformer.

In general, transformers are cooled either by free circulating air or by air blast from a blower. The cooling method used will depend on the CAPACITY of the transformer, and WHERE IT IS TO BE USED.

The smaller transformers of less than 25 kv. amp. capacity—including most of the instrument transformers—are usually AIR COOLED. That is, the heat is taken away by the NATURAL CIRCULATION OF THE AIR.

Larger capacity transformers located in places where oil is considered a fire hazard are cooled by AIR BLAST. The transformer is placed over an air chamber, and the air pressure is maintained by a blower.

POLARITY OF TRANSFORMERS

Before transformers can be connected for either series or parallel operation, it is necessary to know their polarity. You remember when paralleling alternators it is necessary to have the CORRECT POLARITY to prevent one machine becoming a short circuit on the other. Well, the same precaution must be taken with transformers. If the polarity isn't correct, the transformers will be burned out.

You know, of course, that the polarity of the a.c. current in the windings is rapidly changing. However, the secondary always changes with the primary, and LIKE POLARITY of the primary and secondary may be determined for any INSTANT of any alternation. LIKE polarity means that one primary and one secondary are both MAXIMUM POSITIVE at the SAME INSTANT, while at the same instant the other primary and other secondary terminal are MAXIMUM NEGATIVE. That's all there is to transformer polarity. The terminals or leads may be marked to indicate their likeness of polarity. These marks are called polarity markings.

Nearly all modern transformers have their high and low voltage leads marked. Generally, the high voltage leads are marked H_1 and H_2, and the low voltage leads are marked X_1 and X_2, as shown in figure 159*A* and 159*B*. These marks indicate the RELATIVE POLARITIES of the windings. The marks which have the SAME SUBSCRIPTS have the SAME POLARITY at any instant. For example, H_1 and X_1 are maximum at the same time. These marks are used when connecting two or more transformers in parallel or series.

If the transformer leads aren't marked you must mark them. The high voltage leads are usually brought out on one side of

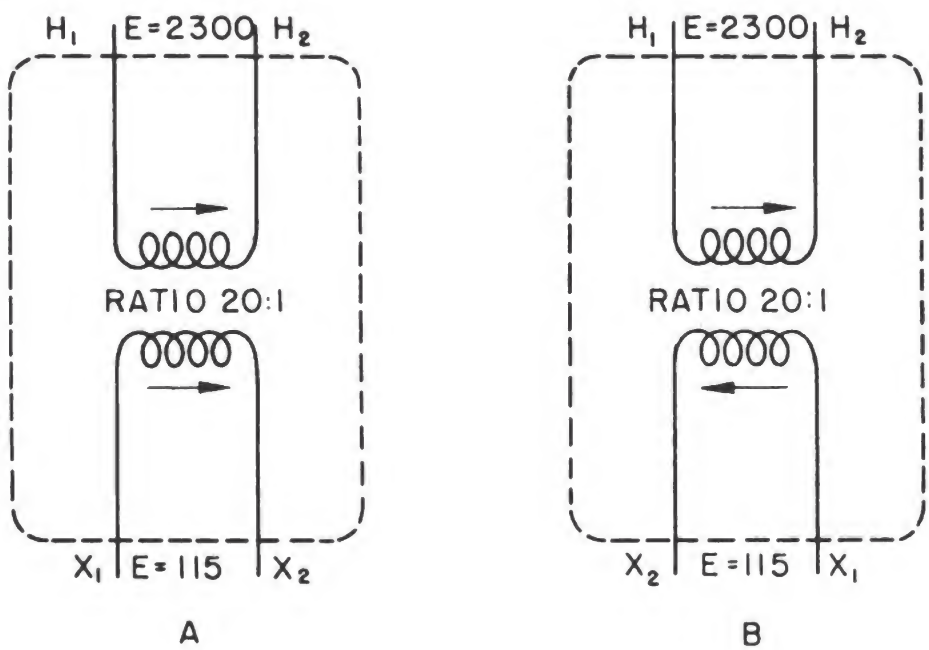


Figure 159.—Transformer polarity markings.

the transformer and the low voltage leads are brought out on the opposite side.

The accepted method for marking the HIGH VOLTAGE primary and secondary leads is—FACE the HIGH VOLTAGE side of the transformer and mark the RIGHT HAND LEAD H_1. The other high voltage terminal is marked H_2.

To mark the other leads, connect the primary of the transformer to the line. Connect one lead of the primary to an adjacent lead of the secondary as shown in figure 160*A*. Excite the primary and take a voltage reading across the other primary and secondary leads. If the voltmeter reads the SUM of the voltages of the two windings, the two windings are connected in SERIES—the voltages ADD together—and the polarity of the low voltage leads would be marked as shown in figure 160*A*. The X_1 lead is diagonally opposite the H_1 lead, and the transformer is said to have ADDITION POLARITY.

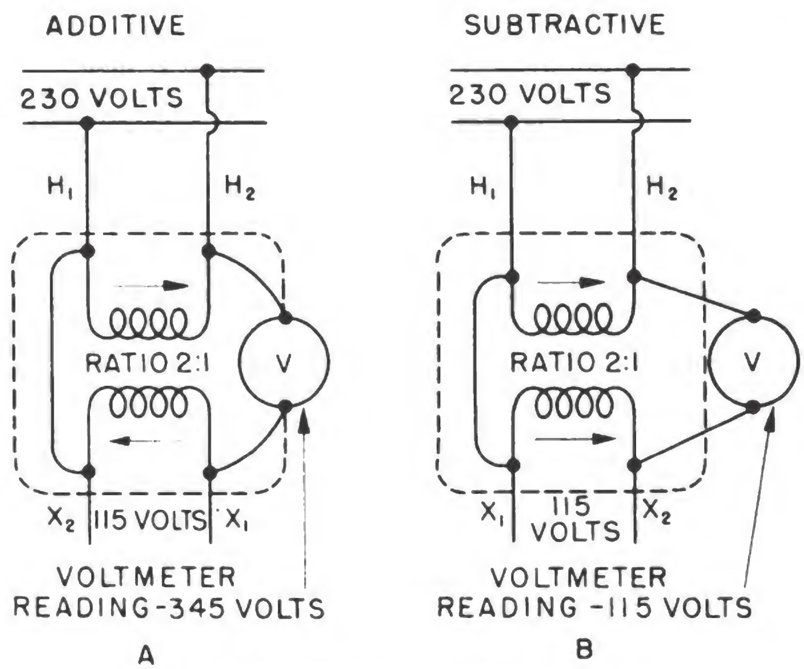


Figure 160.—Method of checking polarity.

If the voltmeter indicates the DIFFERENCE between the voltages of the two windings, they are connected so that their voltages oppose or subtract. That means the like polarities are connected together (figure 160*B*). So, X_1 is adjacent to H_1, and the transformer is said to have SUBTRACTIVE POLARITY.

Don't let that subtractive additive polarity designation throw you. These terms are only used to identify certain conditions. ADDITIVE POLARITY tells you that the high and low voltage leads diagonally opposite each other have the same polarity. And SUBTRACTIVE POLARITY tells you that adjacent high and low voltage leads have the same polarity.

Whether the transformer is additive or subtractive polarity doesn't affect the operation of the transformer. The important thing is to have the polarity marks correct before connecting the transformer for series or parallel operation.

PHASING SPLIT WINDINGS

Many transformers are constructed with two or more windings on the secondary, and some have two or more windings on both primary and secondary. By connecting either the primary or secondary windings in series or parallel, different voltage and current capacities may be obtained from the transformer.

Before these windings can be connected for series or parallel operation, the polarities must be known. A typical system of marking polarities is shown in figure 161. In this case, H_1 and

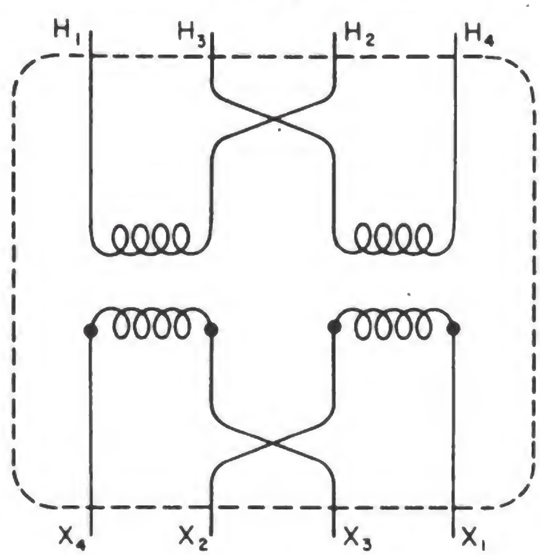


Figure 161.—Identification of leads in a split-primary, split-secondary transformer.

H_4 indicate the END LEADS or terminals for the full winding. For series operation of the high voltage winding, H_2 and H_3

would be connected together and H_1 and H_4 connected to the supply line. For parallel operation, H_1 and H_3 would be connected together and connected to one side of the supply, while H_2 and H_4 would be connected together and connected to the other side of the supple line. The same method would be used for connecting the low voltage windings for series or parallel operation.

PHASING OUT

If the leads aren't marked, then it is necessary to determine their polarities. The process of checking the polarities is called PHASING OUT the windings.

To illustrate phasing out, suppose a transformer has two unmarked 110 volt windings on its primary and you wish to connect them in series so that the transformer may be connected to a 220 volt supply. Proceed as follows—

If there is a 110 volt a.c. supply available, connect one winding to it as shown in figure 162. Since the other winding is on

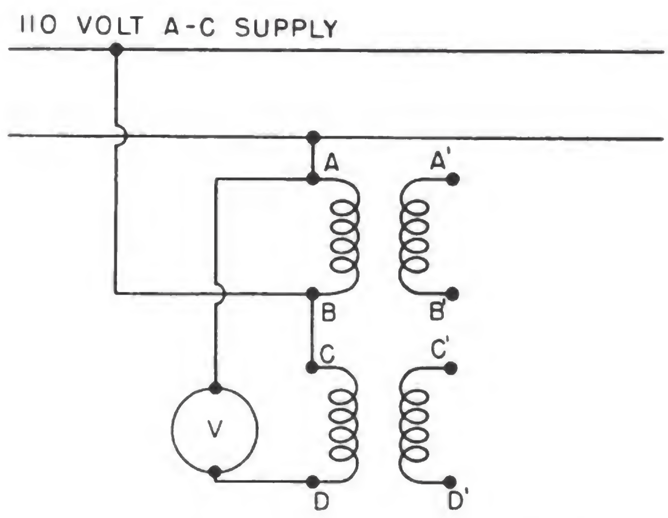


Figure 162.—Method of phasing out transformer coils.

the same core and has the same voltage rating, it will have approximately 110 volts induced in it. Connect on lead C of the winding CD to B of winding AB. If the two windings are in series, a voltmeter across leads AD will read 220 volts—the

sum of the voltages of the two coils—and the connection is correct for series operation. Connections C and B are secured together and leads A and D are connected to the 220 volt line.

The same test may be used for checking the relative polarities of both the primary and secondary windings of transformers. It just happens that both windings are primary in this instance.

If, in the above experiment, the voltmeter reads zero, then leads C and D would have to be switched to get a series connection. However, a zero reading of the voltmeter would indicate the proper connection for paralled operation—C and D would be connected to one side of the supply line and A and B to the other side.

If a 110 volt supply is not available, 220 volts can be used to phase out the windings. Figure 163 shows how the primary is connected to the 220 volt line for the test. Two leads, B and C—one from each winding—are connected together. The other

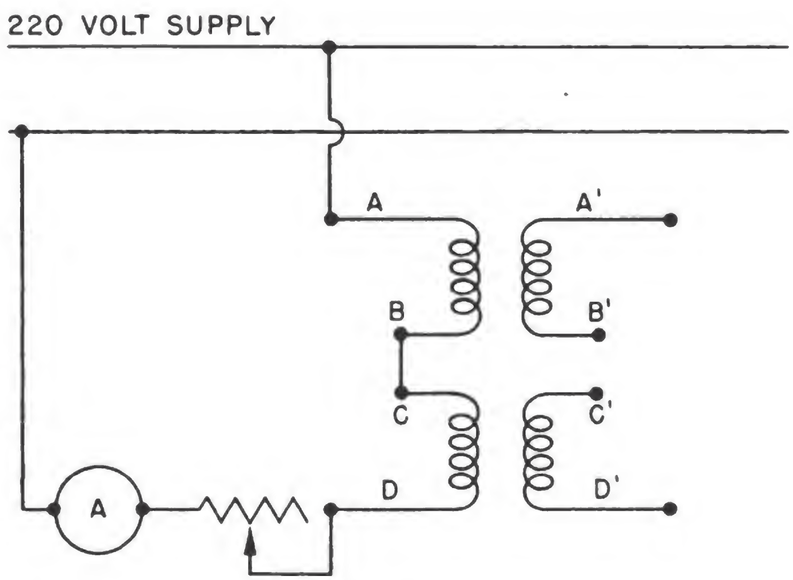


Figure 163.—Phasing out 110 volt primary with 220 volts.

two leads are connected to the 220 volt supply, with a resistance or inductance and an ammeter in the line. The purpose of the resistance is to protect the windings from a short circuiting connection.

When the power is turned on, if the ammeter reads RELATIVELY LOW the windings are PROPERLY CONNECTED for series

operation. The ammeter and resistance or inductance can now be removed.

However, if the ammeter reads a larger current, equal to approximately E divided by the added R or X_L, the windings are NOT properly connected for series operation. Two of the leads must be switched before trying to operate the transformer on the 220 volt line.

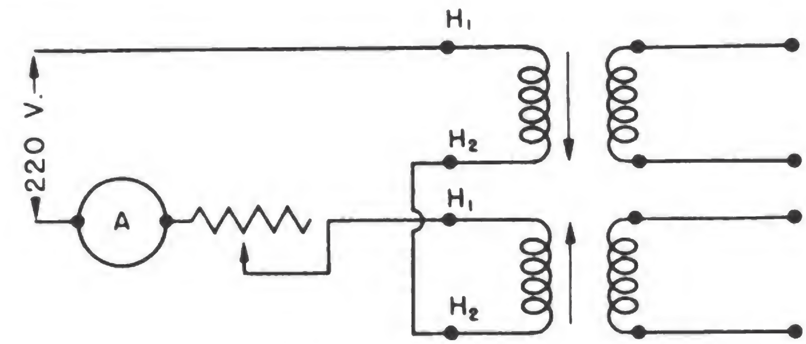


Figure 164.—In correct connection for series operation of transformers.

Figure 164 illustrates the condition which exists when the ammeter reads the higher current. The two leads connected together represent the same polarity at any instant, and, by your hand rule for solenoids, the flux fields of the two windings are

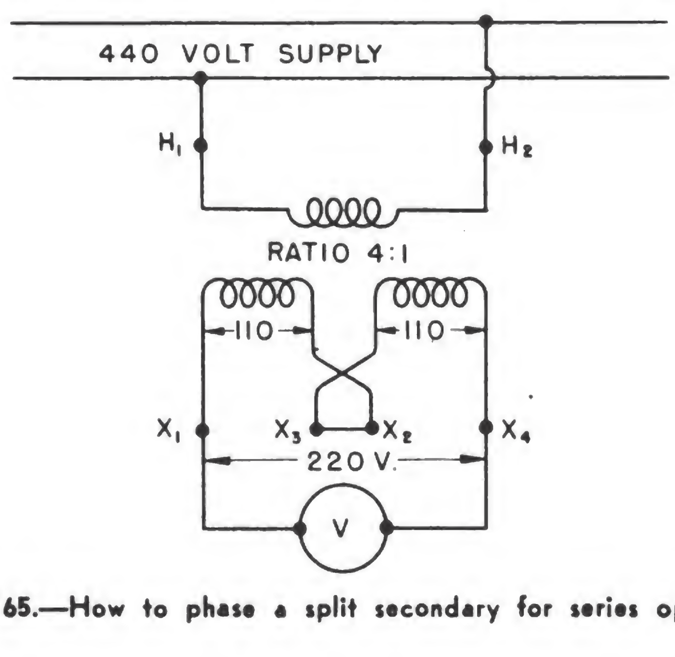


Figure 165.—How to phase a split secondary for series operation.

opposing each other. The total flux is zero, and therefore the Z of the two windings is very low, being only the R of the coils.

Thus, the circuit is virtually a short circuit. The current is limited only by the extra resistance placed in the circuit, whereas in the proper series connection the current is limited by the extra resistance and the high impedance of the two windings.

A transformer with two windings on its secondary is often called a SPLIT SECONDARY transformer. Figure 165 shows how the split secondary is phased out.

Connect two leads—one from each coil—together, and connect a voltmeter or set of test lamps between the other leads. Excite the primary. If the voltmeter reads the sum of the voltages of the two windings the coils are properly connected for series operation. The two leads to which the voltmeter is attached for the test are the lines to connect to the load.

However, if the voltmeter fails to indicate a voltage, the windings are connected for parallel operation. One load line is connected to the leads that are already connected together, and the two leads connected to the voltmeter are joined together and to the other load line as shown in figure 166.

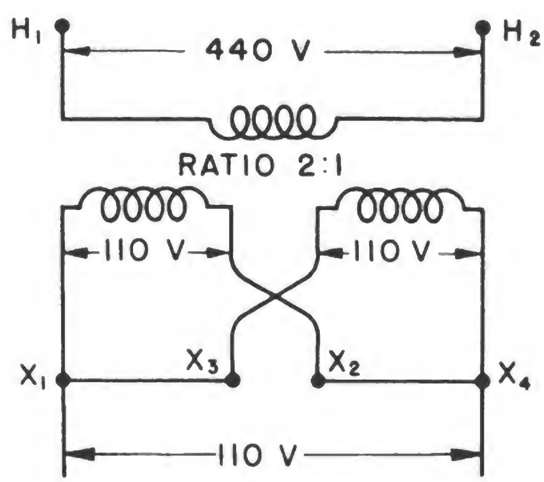


Figure 166.—How to connect a split secondary for parallel operation.

THREE PHASE CONNECTIONS

So far, the transformers discussed have been single phase, used to raise or lower single phase voltages. But, most alternators are THREE PHASE jobs, in which it is often desirable to step-up or step-down the voltage delivered.

A single phase transformer can be used to raise or lower one phase of a three phase voltage. So, to transform three phase voltages, THREE SINGLE PHASE transformers are needed—one for each phase. Although that isn't the only way the job can be done, it is the most easily understood and will be discussed first.

When three transformers are used, there are two common ways of connecting them—STAR and DELTA. These are the same connections used in the alternators which generate three phase voltages.

The current and voltage ratios for star and delta connected transformers are the same as were described earlier for star and delta connected alternators. However, they are given again to refresh your memory. For the STAR connection—

Line I = Phase I

Line E = Phase E $\times$ 1.73

Phase E = Line E $\div$ 1.73

and for the DELTA connection—

Line I = Phase I $\times$ 1.73

Phase I = Line I $\div$ 1.73

Line E = Phase E

Remember that the star connection always increases the line voltage above the phase voltage, and the delta connection always increases the line current above the phase current.

In connecting the transformers, the three primary windings and the secondary windings can be connected either star or delta. If both the primary and secondary windings are connected star, the connection is called a STAR-STAR connection. If both windings are connected delta, the connection is called a DELTA-DELTA connection. If the primary is star and the secondary delta, the connection is a STAR-DELTA connection. If the primary is delta and the secondary star, it is a DELTA-STAR connection.

You will notice that in referring to these connections the PRIMARY is MENTIONED FIRST—just as in speaking of the ratio between the primary and secondary windings.

STAR-STAR CONNECTION

Figure 167 shows three single phase transformers connected STAR-STAR. You will notice that these transformers have polarity markings. To make a star connection, simply connect together three terminals which have the same polarity marks. The other three terminals are connected in order to their respective phases—primary to supply and secondary to load line. By tracing this connection from each line wire through the phase windings, you will find it results in a star-shaped connection as shown in the small simplified sketch at the left of figure 167.

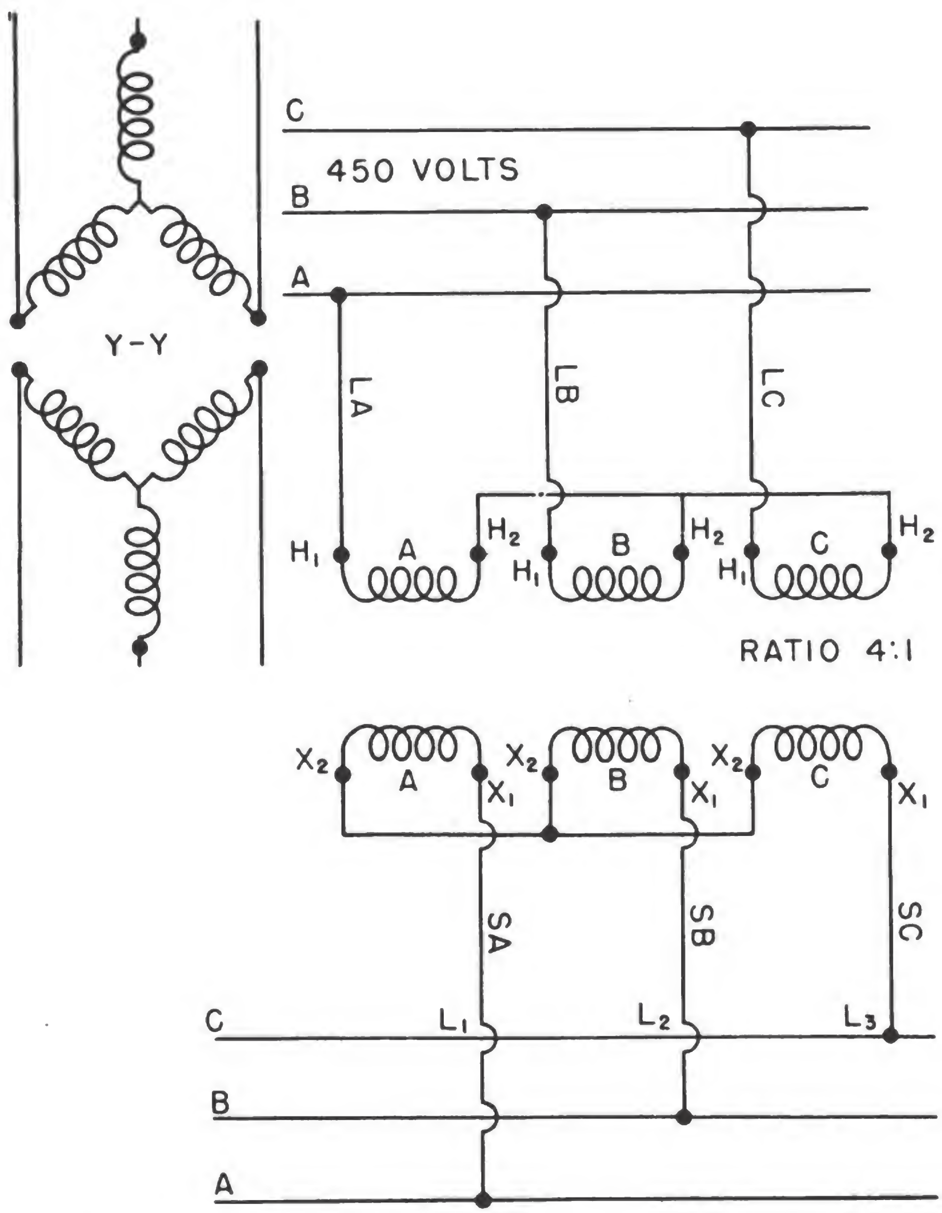


Figure 167.—Three transformers connected STAR-STAR.

If the transformers have no polarity markings, you must check and mark the polarities before making the connection. Or, you can use the following procedure—

Connect three primary leads together—one from each transformer—and connect the three remaining leads to the supply line. Then phase out the secondary windings. To do this, connect two of the secondary windings together as shown in figure 168. Excite the primary and measure the voltage across

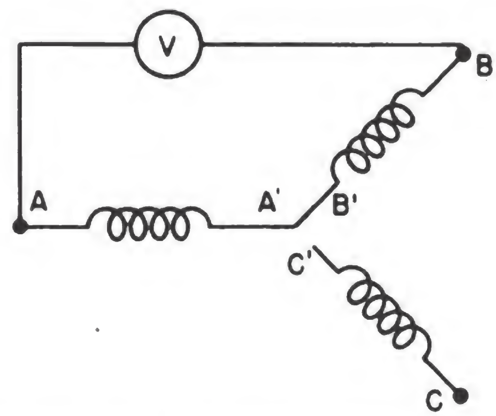


Figure 168.—Phasing out three transformer secondaries for star connection.

the open ends of the secondary windings. If the voltage is 1.73 times the phase voltage—voltage across one winding—the two windings are properly connected for a star connection.

If the voltmeter reads a voltage equal to the phase voltage, one of the windings should be reversed.

Next, connect one lead of the third transformer winding to the point of connection of the two windings that were just tested and properly connected. Read the voltage across the OPEN end of this transformer and the OPEN ends of each of the other two. If it is 1.73 times the phase voltage, the connection is correct. If it is equal to the phase voltage, switch the leads of the third winding. Now the transformers are connected STAR-STAR and the three open leads of the secondary can be connected to the load line.

In figure 167, the primary phase voltage is the voltage between the H_1 and H_2 terminals of any one transformer. Similarly, the secondary phase voltage is the voltage between X_1 and X_2 of any one transformer.

The primary line voltage is the voltage between leads *LA* and *LB*, *LB* and *LC*, and between *LC* and *LA*. This is the same as the voltage between any two of the three phase wires *A*, *B*, and *C*.

The secondary line voltage can be measured between leads *SA* and *SB*, *SB* and *SC*, and between *SC* and *SA*. Or it can be measured between any two of the three phase wires *A*, *B*, and *C* on the secondary.

HERE IS AN EXAMPLE

To help you to understand the various voltages and current values of the secondary and primary lines and phases, the following example is given.

The transformers in figure 167 have a ratio of 4:1. The primary line voltage is 450 volts and the primary line current is 30 amperes. Find the primary phase voltage and current, the secondary phase voltage and current, and the secondary line voltage and current.

The primary is star connected. So, the primary phase voltage is equal to the line voltage divided by 1.73, that is—

Primary phase $E = 450 \div 1.73 = 260.7$ volts (across each primary winding).

Since the ratio is 4:1—

Secondary phase $E = 260.7 \div 4 = 65.1$ volts (across each secondary winding).

The secondary is star connected, so—

Secondary line $E = 65.1 \times 1.73 = 112.5$ volts (voltage across any two lines).

The primary phase current is equal to primary line current or 30 amperes since this is a star connection.

In a transformer the current is increased in the same proportion the voltage is decreased, therefore—

Secondary phase $I = 4 \times 30 = 120$ amperes (flowing in any winding).

Secondary line current is equal to secondary phase current, or 120 amperes.

To check, remember that the power output of the secondary

is equal to the power input to the primary. So, at unity power factor—

$$1.73 \times 450 \times 30 \times 1 = 1.73 \times 112.5 \times 120 \times 1$$
$$23{,}355 \text{ kv. amp.} = 23{,}355 \text{ kv. amp.}$$

DELTA-DELTA CONNECTION

If you trace the connection in figure 169, you will find it results in the Δ-shaped connection shown in the simplified diagram at the left of the figure. There, three transformers are connected DELTA-DELTA.

To connect the primary delta, H_1 of winding A is connected to H_2 of winding B, H_1 of winding B is connected to H_2 of winding A, and H_1 of winding C is connected to H_2 of winding B. That closes the three windings in a delta connection. The three points of connection are connected to the three wires of the three phase voltage line.

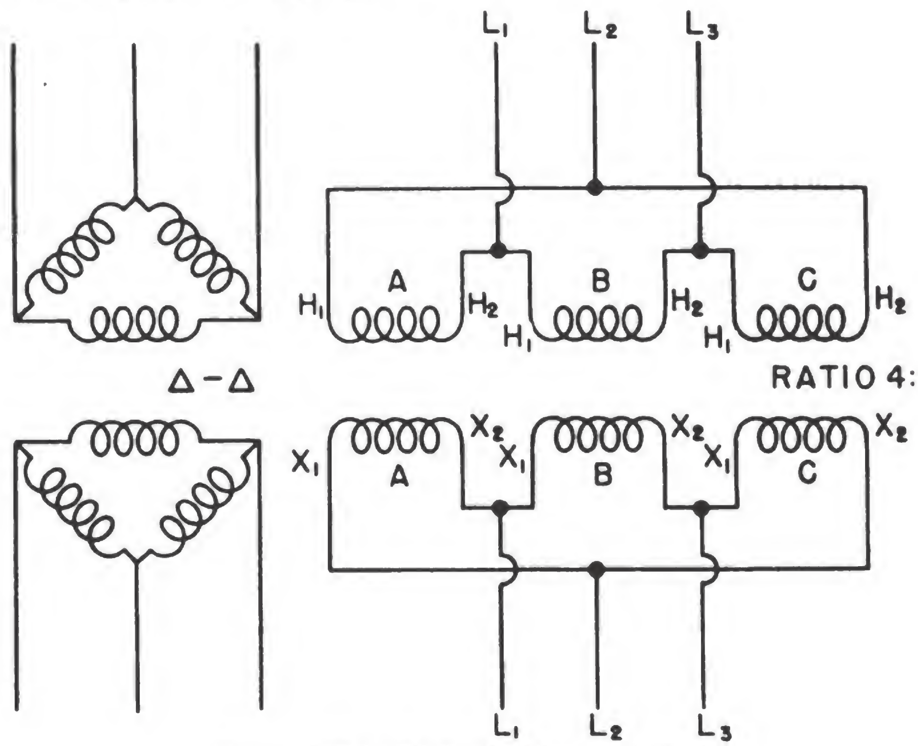


Figure 169.—DELTA-DELTA connection.

The secondary windings are connected in the same manner as the primary windings, and the three leads go to the load line.

If there are no polarity markings on the transformers, the three primary windings are connected delta without any atten-

tion to polarity. Then the primary is connected to the supply and the secondary windings are phased out, as shown in figure 170.

First conect the leads of winding *A* and *B'*. When the primary is excited, the voltage across the open ends of windings *AA'* and *BB'* should be equal to the phase voltage, in which case the windings are properly connected. If it is greater than phase voltage, one winding should be reversed.

When *AA'* and *BB'* are properly connected, connect lead *C* of *CC'* to the open end *A'* of winding *AA'*. The voltage across the open ends *C'* and *B* should be zero, or practically zero. If it isn't, reverse the connections of winding *CC'*. Remember,

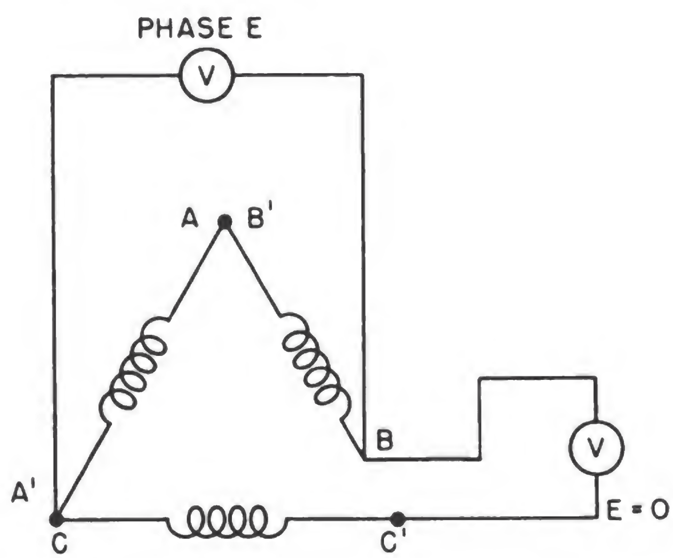


Figure 170.—Phasing three transformers for delta connection.

the SUM of the VOLTAGES around the delta must be ZERO or PRACTICALLY ZERO, otherwise a heavy short circuit current will flow in the windings. When the voltage reading is practically zero, remove the voltmeter and close the delta.

A PROBLEM TO ILLUSTRATE

The following problem illustrates the various current and voltage values in the primary and secondary lines and phases for a delta-delta connection. The problem uses the same values that were used in the star-star connection—primary line voltage

is 450 volts, primary line current is 30 amperes, and the ratio is 4:1.

The primary is connected delta, so PRIMARY PHASE VOLTAGE EQUALS PRIMARY LINE VOLTAGE, or 450 volts.

Since the ratio is 4:1—

Secondary phase $E = 450 \div 4 = 112.5$ volts (voltage across any winding).

Primary line current is 1.73 times phase current, so—

Primary phase $I = 30 \div 1.73 = 17.3$ amperes (current in any winding).

The turns ratio is 4:1, so—

Secondary phase $I = 17.3 \times 4 = 69.2$ amperes (current in any winding).

Secondary line $I = 69.2 \times 1.73 = 120$ amperes (current in any line).

You will notice that in both the star-star and delta-delta connection the ratio between the primary line voltage and the secondary line voltage — 450:112.5 = 4:1 — is the same as the ratio between the windings. Thus, with either of these connections, it is possible to find the line voltages and currents without using the phase values. For example, if the primary line voltage of a star-star connected transformer bank is 4,000 volts and the ratio is 10:1, the secondary line voltage is $4{,}000 \div 10 = 400$ volts.

STAR-DELTA CONNECTION

Figure 171 shows a three-phase transformer bank connected STAR-DELTA, with the primary windings connected star and the secondary windings connected delta. To compare the various voltages and currents of the lines and phases with the corresponding values of star-star and delta-delta connections, solve the same problem that was used before—the primary line voltage is 450 volts, primary line current is 30 amperes, and the ratio is 4:1. The other values are—

Primary phase $E = 450 \div 1.73 = 260.7$ volts.

Secondary phase $E = 260.7 \div 4 = 65.1$ volts.

The secondary is connected delta so—

Secondary line $E = 65.1$ volts.

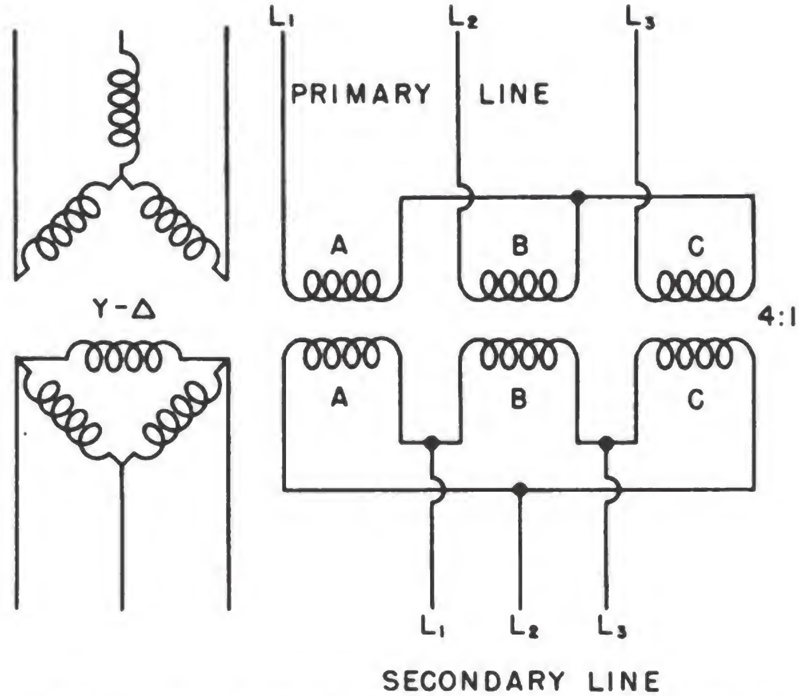


Figure 171.—A STAR-DELTA transformer connection.

Notice that this voltage, 65.1 volts, is lower than was obtained in the star-star or delta-delta connection, although the ratio of the transformers is the same.

The primary line current is 30 amp., so—

Primary phase I = 30 amp.

Secondary phase I = 4 × 30 = 120 amp.

Secondary line I = 120 × 1.73 = 207.6 amp.

This secondary line current is higher than was obtained on the star-star or delta-delta connections.

DELTA-STAR CONNECTION

Figure 172 shows a three phase transformer bank connected DELTA-STAR. This connection is just the opposite of the connection in figure 171.

To compare the results obtained from this connection, assume the same values that were used for the other connection—450 volts and 30 amperes on the primary line and a 4:1 ratio.

The primary is delta connected; therefore—

Primary phase E = 450 volts

Secondary phase E = 450 × 4 = 112.5 volts

Primary phase $E = 30 \times 1.73 = 17.3$ amp.
Secondary phase $I = 17.3 \times 4 = 69.2$ amp.

The secondary is connected star, so—
Secondary line $E = 112.5 \times 1.73 = 194.6$ volts
Secondary line $I = 69.2$ amp.

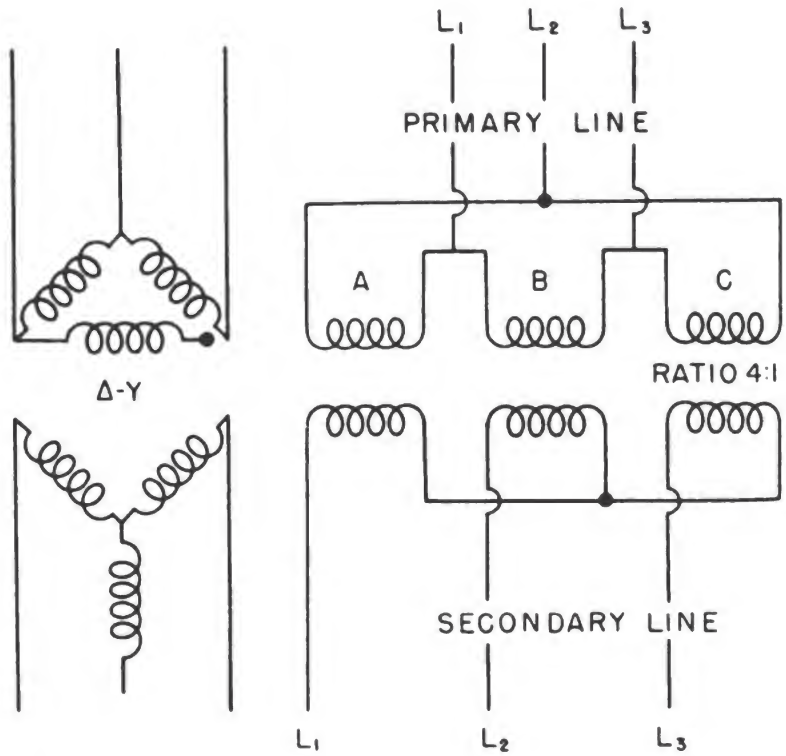


Figure 172.—A DELTA-STAR transformer connection.

You will notice that the SECONDARY LINE VOLTAGE IS HIGHER THAN IN ANY OF THE OTHER CONNECTIONS, and the transformer ratios are the same. For that reason the delta-star connection is often used to step-up voltages for transmission. It is possible in this way to get a high secondary voltage with a small turns ratio.

OPEN DELTA OR V CONNECTION

If you removed one of the transformers from a delta-connected transformer bank, you would have the circuit shown in figure 173. What's more, this connection would continue to deliver a three phase voltage. It is known as the OPEN DELTA or V connection.

Probably the first thing you want to know is how this connection can deliver a three phase voltage. Well, with a little help you can answer that for yourself.

Take another look at figure 173. You know the voltage between lines *A* and *B* is equal to the voltage across phase *AB*,

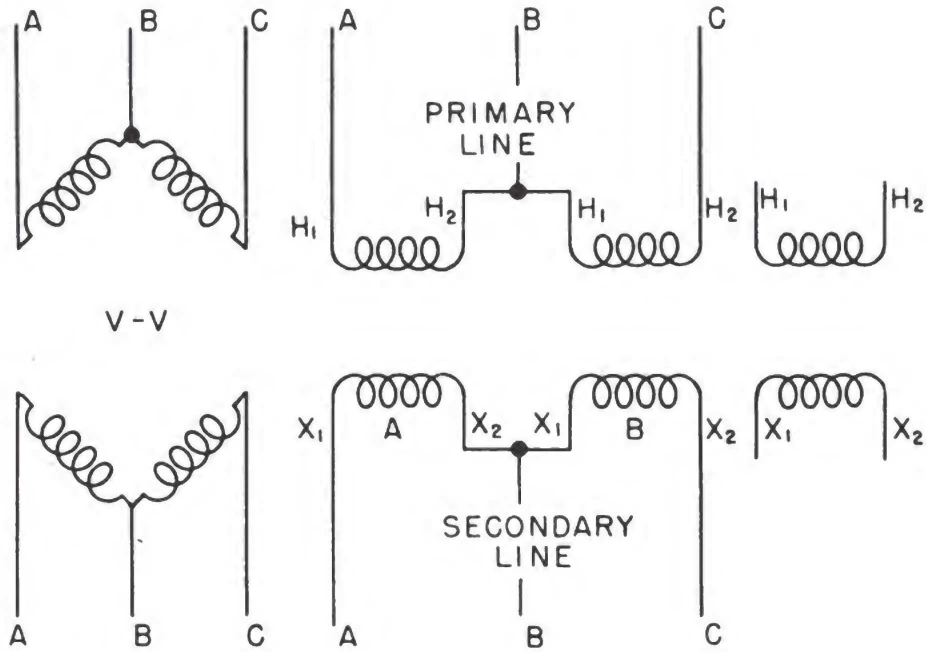


Figure 173.—An open delta transformer connection.

and the voltage between lines *B* and *C* is also phase voltage. It was pointed out—in phasing windings for delta connections —that a VOLTAGE EXISTS BETWEEN lines *C* and *A*, and this voltage is EQUAL to PHASE VOLTAGE. Thus you have a three phase voltage being delivered by two transformers connected open delta.

The two transformers connected open delta deliver the three phase voltage, but they can not deliver as much power as three transformers of the same individual rating and connected delta.

At first thought, you would probably expect the open delta connection to have two-thirds the capacity of the delta connection. However, this is not the case. The kv. amp. capacity of the open delta is approximately 57.7% of the delta connection having individual transformers of equal rating. This can be proved as follows—

By observing figure 173, you will see that in an open **delta** conection the LINE CURRENT IS EQUAL TO THE PHASE CURRENT. This means that in order not to overload transformers the **line** current must not exceed the rated current of the individual transformer.

In the closed delta connection at unity power factor, full load capacity is—

$$P = 1.73\ E_1 I_1$$

Where—

E_1 = line voltage
I_1 = line current at rated load

The RATED CURRENT of the individual transformers—PHASE CURRENT—is $\dfrac{I_1}{1.73}$. Thus in the open delta connection, the line current as compared to the line current of the delta is $\dfrac{I_1}{1.73}$. So the rated capacity of the open delta connection is—

$$P = 1.73\ E_1 \times \frac{I_1}{1.73} = E_1\ I_1$$

as compared to the delta connection. Therefore, the load which the two transformers can carry when connected in the open delta is—

$$E_1\ I_1 + 1.73\ E_1\ I_1 = \frac{1}{1.73} = .577 \text{ or } 57.7\%$$

In other words—57.7% of the load which these transformers could carry when connected delta.

ANOTHER EXAMPLE

To illustrate further, suppose that three 10 kv. amp., 230 volt, single phase transformers are connected delta. The ampere rating of each transformer is—10,000 ÷ 230 = 43.5 amperes.

The line current, when each transformer is carrying full load, is 43.5 × 1.73 = 75.3 amperes. So the total load which could be carried by the delta connection without overloading the transformers would be—

1.73 × 75.3 × 230 = 30,000 volt-amperes or 30 kv. amp.

If one transformer were disconnected, the remaining two, connected open delta, could carry 43.5 amperes without being overloaded. Also, 43.5 amperes would be the line current. Therefore, the total load of the open delta connection would be—

$$1.73 \times 43.5 \times 230 = 17,310 \text{ volt-amperes or } 17.31 \text{ kv. amp.}$$

Thus the load which is carried by the open delta connection is—

$$17.31 \div 30 = .577 \text{ or } 57.7\%$$

Again, 57.7% of the load which is carried by the delta connection.

Furthermore, instead of the two transformers carrying their rated load of 20 kv. amp.—10 kv. amp. each—in open delta they can carry only 17.31 kv. amp. or—

$$17.31 \div 20 = .8655$$

Or, 86.55% of their rating without being overloaded.

AN ADVANTAGE FOR THE DELTA

In a delta connection, if one transformer is damaged it may be discontinued or removed for repair, and the system can still operate at 57.7% of capacity. But in a star connection, if one transformer is damaged or removed it isn't possible to operate the system.

THIS ADVANTAGE FOR THE STAR

A transformer for a delta connection must be designed for full line voltage, but a transformer in a star connection is designed to carry only 57.7% of full line voltage. So for very high voltages, transformers designed for star connections are less expensive to build because they require less insulation.

AUTO TRANSFORMER

Figure 174 shows a diagram of an AUTO-TRANSFORMER. It has only one winding. Thus it is different from the transformers you have already studied. It also differs in another way—only a part of the power delivered from the source of supply to the secondary load is transformed into power. How-

ever, like the other static transformers, it is used to step-up or step-down voltage.

In figure 174, the winding AC is connected across a voltage supply of 100 volts; B is the midpoint of winding AC, so the voltage BC is 50 volts.

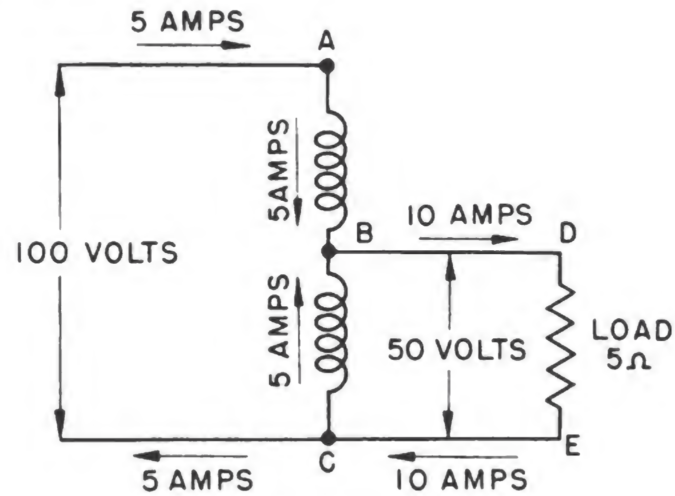


Figure 174.—Auto-transformer.

The secondary load of five ohms is connected between lines BD and CE. Since the voltage across the load is 50 volts, the current is 10 amperes — $50 \div 5 = 10$ amp.

The ratio of the secondary voltage to the primary voltage is $E_{BC}:E_{AC} = 50:100$ or $1:2$. Therefore, the primary current must be five amperes — $I_p:10 = 1:2$.

Thus, when there are 10 amperes flowing in the load, there are five amperes flowing from the source through the primary lines and primary windings. Losses are negligible and are not considered, in order to simplify the explanation.

The arrows indicate an instantaneous direction of currents. The five amperes supplied by the source at a voltage of 100 volts flows through winding AB, undergoing a drop in potential of 50 volts, through the load DE, undergoing another drop in potential of 50 volts, and back to the source. (The resistance of the lines has been ignored.)

Thus, 250 watts of power — $50 \times 5 = 250$ — have been delivered to the load from the source by conductivity.

But what becomes of the 250 watts across winding AB? It isn't wasted. The power represented by this current undergoing

a drop in potential from A to B is transferred to the magnetic field. The power transferred to the magnetic field appears in the winding BC, where a current of five amperes has raised 50 volts in potential. This is transformer action and, actually, AB is the primary of the transformer and BC is the secondary. The load is connected across BC. And the 250 watts of transformed power is added to the 250 watts of conducted power. Thus a total power of 500 watts is supplied the secondary load at 50 volts and 10 amperes from a source of 100 volts and five amperes.

The winding doesn't have to be tapped in the center. It may be tapped anywhere. As a matter of fact it may have several taps, thereby making several different voltages available.

Figure 175 shows an auto-transformer with ¾ of the winding tapped for the secondary. If 120 volts are applied to the winding, a secondary voltage of 90 volts is available. If a 20 ampere load is connected across the secondary, 15 amperes

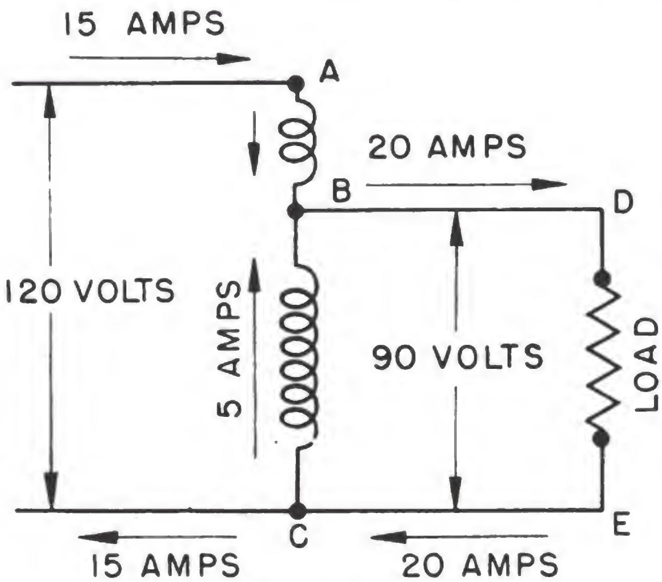


Figure 175.—Auto-transformer.

will flow in the primary. Neglecting losses, there is an input of 1,800 watts to the primary—and 1,800 watts are consumed by the secondary load.

The voltage drop across AB is 30 volts. Therefore, the power represented by the 15 amperes undergoing a drop in potential of 30 volts across AB is 450 watts—$30 \times 15 \doteq 450$. This 450

watts is transferred to winding *BC* by transformer action, and is delivered by BC to the load at 90 volts and five amperes.

Thus, the TRANSFORMED POWER delivered to the load is 450 watts. Therefore, the CONDUCTED POWER must be $1800 - 450 = 1350$ watts. This 1,350 watts represents the 15 amperes which flows directly from the source through the load at a drop in potential of 90 volts — $90 \times 15 = 1{,}350$ watts.

The AUTO TRANSFORMER is sometimes called a COMPENSATOR. It is used extensively in starters for a.c. induction motors. If used in a three-phase starter to start a three phase motor, three of the transformers are connected star—or two of the transformers may be used by connecting them in open delta.

Because the secondary doesn't carry the full load current, it requires less copper. However, as the ratio increases, this saving in copper is reduced; thus, at near 1:1 ratio it requires about the same amount of copper as the regular transformers of the same capacity.

The secondary is connected electrically as well as magnetically to the primary. Hence, there is always the possibility that the secondary may be subjected to the primary voltage. This makes the transformer dangerous when used to step-down high voltage to the common 110 volts.

INSTRUMENT TRANSFORMERS

Suppose you wish to measure the voltage on a 450 volt circuit. Any voltmeter connected directly across the circuit must be insulated to withstand this voltage. It should be evident that this insulation would make the instrument bulky and inaccurate. Furthermore, there would be an element of danger to the operator using an instrument directly across a 450 volt circuit.

But suppose the primary of a 4:1 transformer is connected across the circuit. What is the secondary voltage of the transformer?

That's right, 112 volts. And it would be a simple matter to read this secondary voltage with an ordinary 150-volt voltmeter. That should suggest a method for measuring high a.c. voltage without connecting the voltmeter directly to the line and sub-

jecting the instrument to the high voltages—that's it, step-down the voltage, measure it with an ordinary voltmeter, and multiply the reading by the transformer ratio.

Or, if the voltmeter is to be used continuously with the transformer, have it calibrated to read the high voltage.

POTENTIAL TRANSFORMERS

Transformers designed and used for this purpose are called POTENTIAL TRANSFORMERS or VOLTAGE TRANSFORMERS. Their basic principles of design and operation are the same as for the ordinary static transformer. However, they are smaller and are designed for the highest possible efficiency. The power rating is generally between 40 and 100 watts. The smaller models are air cooled.

Potential transformers are used also to step-down the voltage for devices such as relays and static regulators which do not require a high current.

Figure 176 shows a voltmeter connected through a potential transformer to a high voltage circuit. You should pay par-

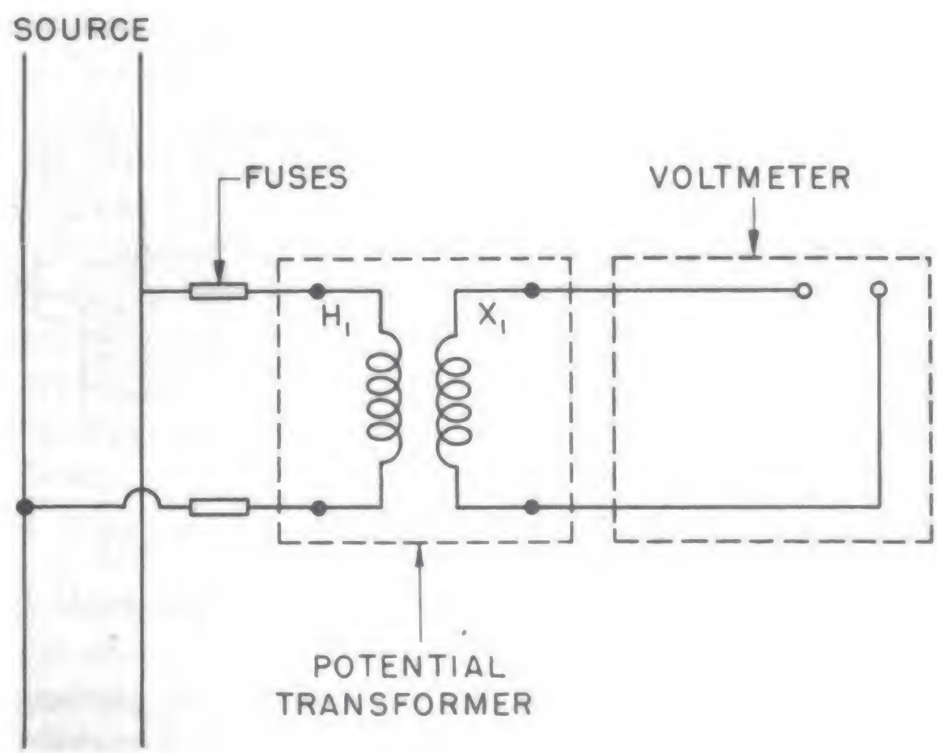


Figure 176.— Diagram of a potential transformer.

ticular attention to the GROUNDING of the secondary of the transformer and to the grounding of the voltmeter. This is done to protect the instrument and the operator, and is a precaution which SHOULD ALWAYS BE OBSERVED.

You will also notice that the primary connections to the line are fused. These fuses are intended primarily to protect the line. However, they do afford some protection to the transformer itself.

CURRENT TRANSFORMERS

It is obvious that an ammeter built to measure several hundred or several thousand amperes which would pass through the instrument itself would be so bulky that it would be inaccurate. On the other hand, if the circuit is delivering a small current at a high voltage, the wires of the coils will not be large and bulky, but must be insulated to withstand the high voltage of the circuit. So, again you find the current-carrying coil will become bulky because of the insulation. Therefore, it becomes very difficult to build an ammeter which will read accurately a high current, or a low current in a high voltage circuit. Fortunately, in a.c. circuits, these difficulties can be overcome by the use of CURRENT TRANSFORMERS.

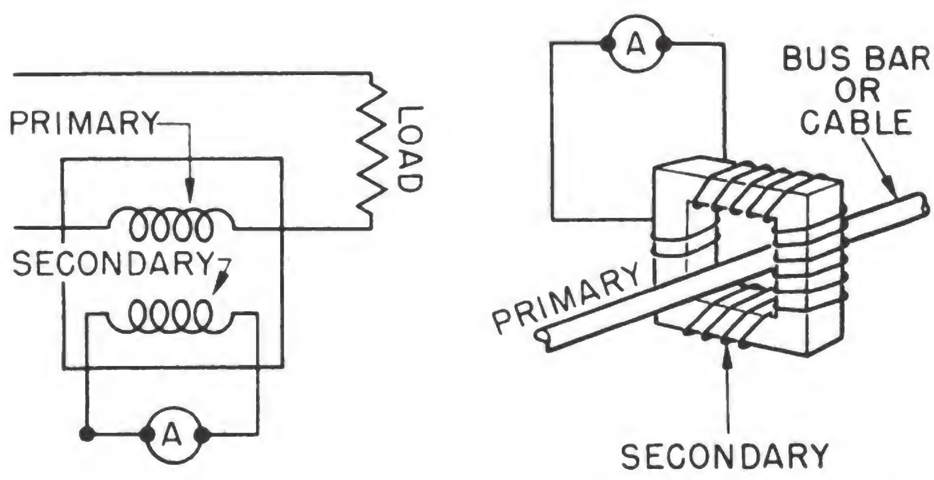


Figure 177.—Circuit for connecting a current transformer to the line.

Current transformers are designed to step-down the current. The primary consists of a small number of turns, wound on a core and connected in series with the lines. Of course, the

coils of the primary must be large enough to carry the line current. And when the primary has a very large current rating it may consist of a STRAIGHT CONDUCTOR or BUS BAR passing through the hollow of an iron core. Both types are shown in figure 177.

The ratio of the secondary current to the line current is approximately the inverse ratio of the turns of the secondary winding to the turns of the primary windings. If the primary has two turns and the secondary 120 turns, the current ratio will be 60:1. So 300 amperes flowing in the line would cause only five amperes to flow in the secondary when it is short circuited. This ratio will vary slightly because of magnetizing current, and the error may be rather large for small currents.

Practically all current transformers are designed so the secondary has a rating of five amperes, regardless of primary rating. For example, a 1,000 ampere current transformer would have a ratio of 200 to 1, and a 100 ampere transformer would have a ratio of 20 to 1.

The ammeters used with the transformer are constructed to carry five amperes and the reading is multiplied by the ratio of the transformer with which it is used. If the ammeter is to be used with only one transformer or with transformers which have the same ratio, it may be calibrated to read the line current.

Unlike the ordinary transformer, the current in the primary of the current transformer is NOT determined by the secondary load. The primary current is determined entirely by the current in the line—that is the load on the system. And, if its secondary is open-circuited, a high voltage is caused to exist across the secondary terminals.

When the secondary is open circuited, the counter ampere-turns no longer exist, and the flux in the core is no longer the difference between the primary flux field and the secondary flux field. Instead, the total flux field of the primary acts on the secondary winding and induces a very high voltage. This high voltage not only may puncture the secondary insulation, but it endangers the life of the operator. For that reason, the secondary of a current transformer should always be short circuited. Never remove the ammeter without first short-circuiting the secondary of the transformer.

Wattmeter and other a.c. instruments may be used with instrument transformers. The VOLTAGE COIL of the instrument is connected to the POTENTIAL TRANSFORMER and the CURRENT COIL is connected to a current TRANSFORMER. The transformers have polarity markings to aid you in connecting instruments to get the proper deflection.

When installing instrument transformers, it is important that the manufacturer's instructions for installation be carefully followed. When connecting the instrument to the secondary of the transformer, be sure the polarity marks match.

After instrument transformers have been installed, they should need no care other than seeing that they are kept clean and dry, and that there are no high resistance contacts.

BE CAREFUL

CAUTION: Always consider current transformers as a part of the circuit to which they are connected. TOUCH ONLY THE SECONDARY LEADS, and see that the transformer is properly

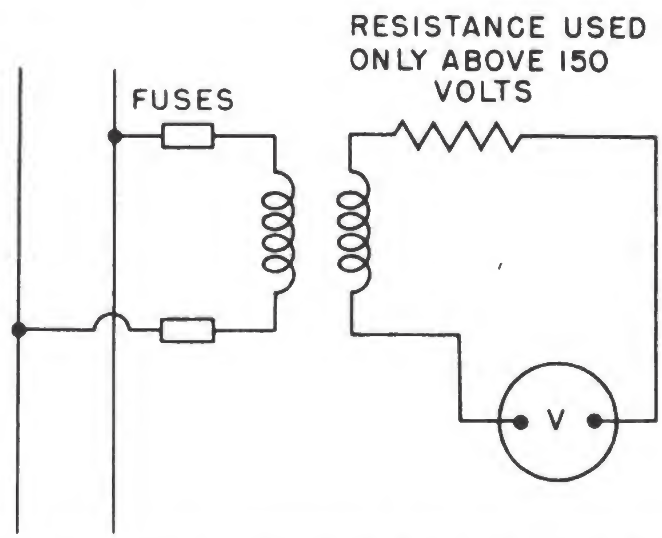


Figure 178.—Potential transformer with a voltmeter using an external resistance.

grounded. NEVER OPEN CIRCUIT THE SECONDARY of the current transformer while the primary circuit is energized.

On the other hand, NEVER SHORT CIRCUIT THE SECONDARY OF A POTENTIAL TRANSFORMER. The instrument may be disconnected from the secondary at any time.

Figures 178 through 180 show diagrams of the connections for instrument transformers used with different instruments

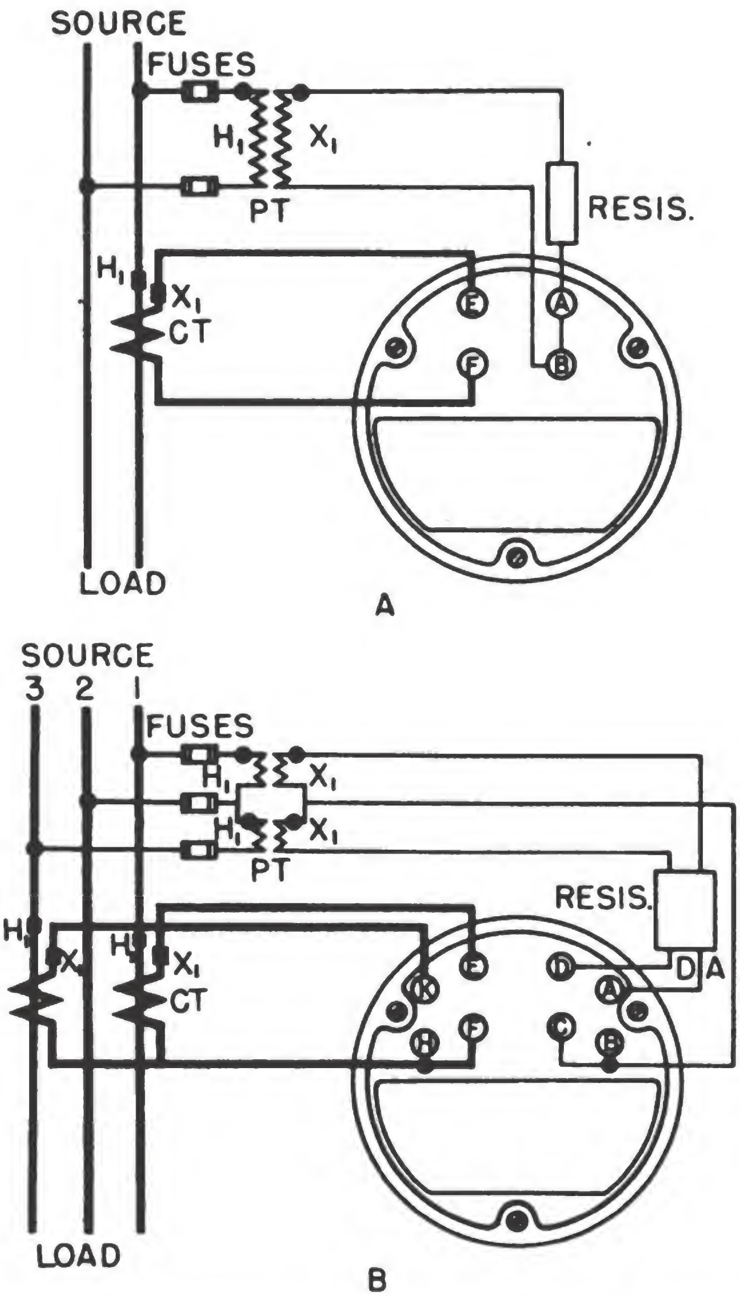


Figure 179.—Connections for single and three phase wattmeter.

and the connections for the instruments. Though not shown on diagrams, you should pay particular attention to the ground connections for the transformer secondaries and for the instrument cases. Also, observe the polarity markings used.

Figure 178 shows an a.c. voltmeter connected for use with a potential transformer. The external resistance is used only when voltages are above 150 volts.

Figure 179*A* shows a SINGLE PHASE WATTMETER connected for use with instrument transformers. The potential coil of the wattmeter is connected to the potential transformer, and the current coil is energized from the secondary of the current transformer.

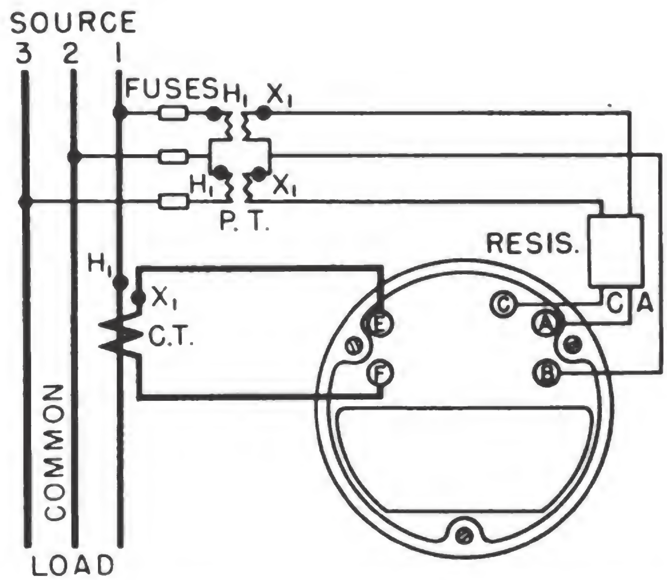


Figure 180.—Connection for a polyphase power factor meter.

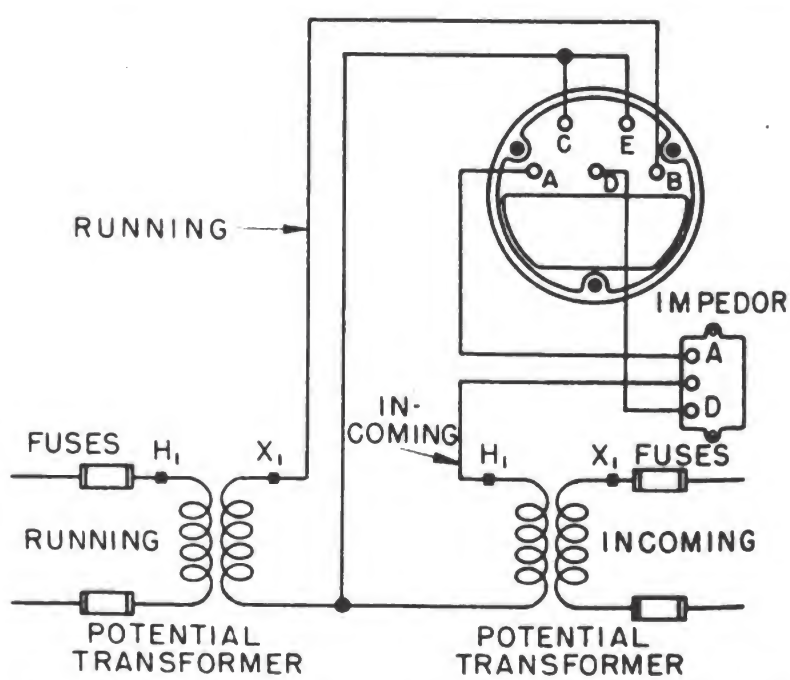
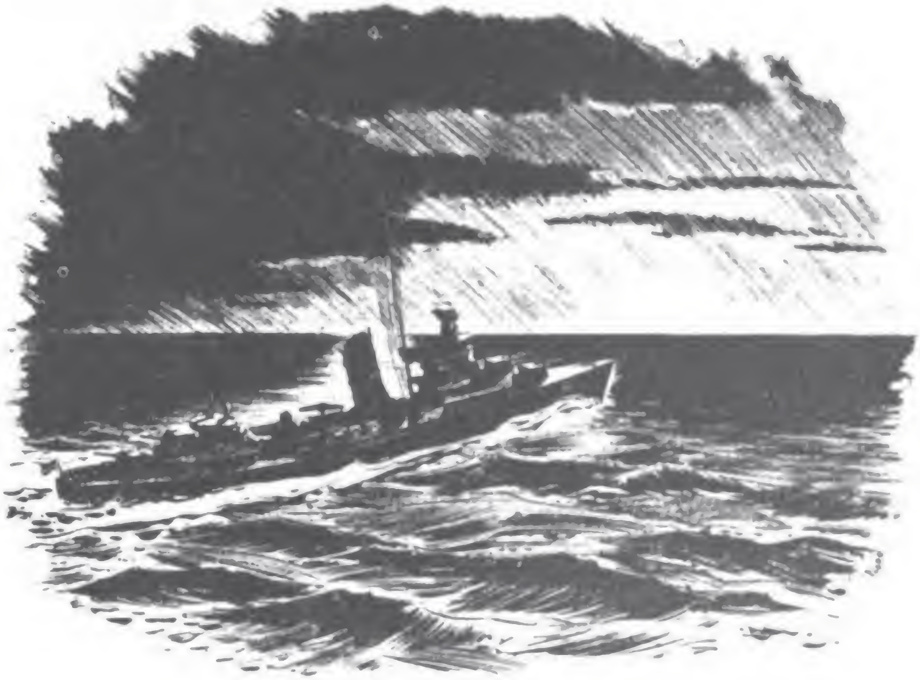


Figure 181.—Connections for a synchroscope and instrument transformer.

Figure 179*B* shows the connections for using a POLYPHASE WATTMETER with instrument transformers. You will notice that the POTENTIAL TRANSFORMERS are connected OPEN DELTA and the CURRENT TRANSFORMERS are connected in the OUTSIDE LINES ONLY. The external resistance is used only for voltages above 150 volts.

Figure 180 shows a diagram for the connection of a POLYPHASE POWER FACTOR METER. The potential transformers are connected in open delta as for the polyphase wattmeter. But only one current transformer is used.

Figure 181 shows the connections for a synchroscope used with potential transformers. Pay particular attention to the polarity marks. The IMPEDOR shown contains the resistance and the inductance which are used with the synchroscope.



CHAPTER 20

A.C. MOTORS

INDUCTION MOTOR

Of all the a.c. motors, the INDUCTION MOTOR is the most widely used. Its design is simple and its construction rugged. Because it does not use a commutator, most of the troubles encountered in the operation of d.c. machines are eliminated. No sparking, no high segments, no bad brushes, no shorted segments—these features appeal to all operators.

The induction motor is particularly well adapted for constant speed jobs, and recent developments have made it possible to adapt the motor to some variable speed jobs. However, except for horsepower ratings less than one, the additional parts for variable speeds are bulky, expensive, and generally inefficient.

The induction motor can be either a single-phase or a polyphase machine. The operating principle is the same in either case, except that single-phase machines require SPECIAL STARTING WINDINGS. Both make use of the ROTATING MAGNETIC FIELD principle to reproduce torque. To understand the oper-

ating principle of the induction motor, you must know what is meant by rotating magnetic field.

ROTATING MAGNETIC FIELD

You can't see the rotating magnetic field, even if you are looking for it. There are no pulleys, gears, or field pieces flying about. But you can see the effects of the field. For instance, if you held a compass in the field, the needle would spin so fast you could see nothing but a blur. This rotating magnetic field is solely the result of SHIFTING THE MAGNETIC FIELD OF THE STATOR.

The stator of an induction motor, like that of an alternator, has no projecting poles. It is DRUM WOUND, with the coils laid in slots in the stator core. The windings are connected just

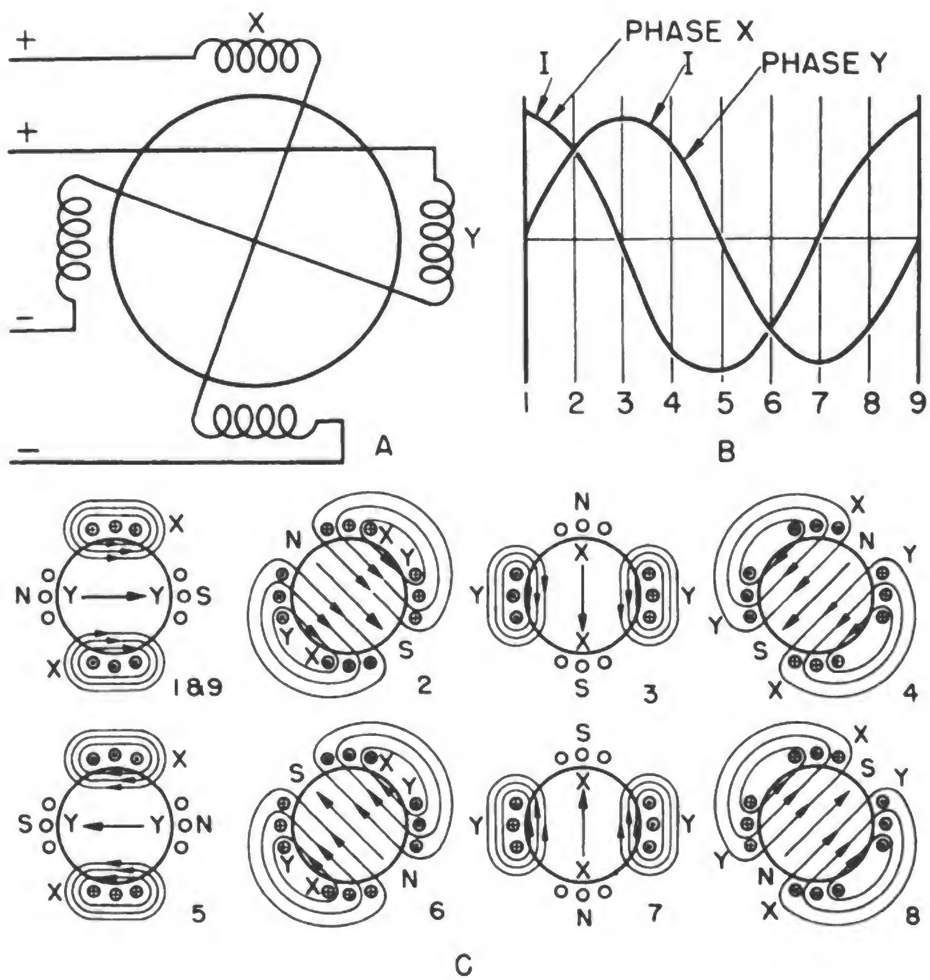


Figure 182.—A two phase, rotary field.

as in the stator of an alternator. In fact, the ordinary alternator winding serves very satisfactorily as a stator winding for an induction motor.

Figure 182*A* is a cross sectional view of a two pole, two phase stator winding. Now suppose this winding is energized by a two phase current. The current will vary as shown by the sine curves in figure 182*B*. As the current varies, so does the magnetic field produced by the current.

At the instant marked 1 in figure 182*B*, the current is zero in phase *Y* and maximum in a positive direction in phase *X*. The resulting magnetic field appears in figure 182*C*. With the current flowing in the direction shown in figure 182*B*, a flux is established which is indicated by the arrows in figure 182*C*.

At position 2, the current is in the same direction in phase *X*, but it has decreased in value. However, the current in phase *Y* has increased in the same direction and is equal to the current in phase *X*. The sum of the instantaneous values of the two currents is always equal to the maximum value of one phase. So, at instant 2, the same value of current is flowing as at instant 1. However, this current at 2 is the vectorial sum of two equal currents 90° apart. Therefore, the resultant current is 45° from the current at position 1. Thus the flux field is still equal to the FLUX FIELD at position 1, but it has SHIFTED 45° in a CLOCKWISE direction to position 2.

At instant 3, the current in phase *X* has decreased to zero and the current in phase *Y* is maximum. The flux hasn't changed in value but it has shifted another 45° in a clockwise direction. At instant 4, the current in phase *X* has reversed and has the same value as the current which has decreased in phase *Y*. The resultant flux has shifted another 45° in a clockwise direction.

At instant 5, the current in phase *X* is again maximum but in the opposite direction to its direction at instant 1. The current in phase *Y* is zero. And the resultant flux has shifted another 45°. The resultant flux field is in a position 180° from its position at instant 1. In other words, the magnetic field has shifted half way around the stator.

Only periods 45° apart have been considered, but you must remember the SUM of the INSTANTANEOUS VALUES of the two

currents is the SAME FOR ALL INSTANTS, and that this vertical sum is a resultant current which shifts in phase relationship to the two currents as their relative values change. You can see that the shift of the magnetic field occurs smoothly and evenly as the values of the currents change.

Diagrams 6, 7, and 8 indicate the shifting of the field flux for the last half of the cycle of the currents; at 9 the flux is back to its original position. During the one cycle of current, 360 electrical degrees, a constant value flux field has made one complete revolution around the stator of a two pole machine. If the frequency is 60 cycles per second, the rotating magnetic field makes 60 rps. or 3,600 rpm, in the two pole machine.

HOW TO FIND THE RPM

If the machine had four poles, 720 electrical degrees, it would require TWO CYCLES of current—twice as long—for the field to make ONE COMPLETE ROTATION. Thus, the number of revolutions per second for the field is equal to the FREQUENCY divided by the number of PAIRS of POLES— $f \div \frac{P}{2} = \frac{2f}{P}$.

There are 60 seconds in a minute, so—

$$RPM = 60 \times \frac{2f}{P} = \frac{120f}{P}$$

$$S = \frac{120f}{P}$$

where, $S = RPM$

$S = \frac{120f}{P}$ isn't a new formula. It is the same one you used to determine the frequency of an alternator. In the alternator, the speed of the field and number of poles determined the frequency of the current in the stator. In the motor, the FREQUENCY of the CURRENT in the STATOR and the NUMBER of POLES determined the speed of the field.

The speed of the rotating field is called SYNCHRONOUS SPEED. It should be obvious that if the frequency of the applied current is increased, the speed of the rotating field increases. Or if the

frequency is decreased, the speed of the field decreases. Furthermore, it should be apparent that if the number of pairs of poles is increased, the speed decreases. To sum it up, the speed of the rotating field—synchronous speed—varies directly as the frequency of the applied voltage and inversely as the number of pairs of poles in the motor.

Thus, on a 60 cycle line, a two pole motor would have a synchronous speed of—

$$S_s = \frac{120f}{P} = \frac{120 \times 60}{2} = 3{,}600 \text{ rpm.}$$

For a four pole machine—

$$S_s = \frac{120f}{P} = \frac{120 \times 60}{2} = 1{,}800 \text{ rpm.}$$

For a six pole machine—

$$S_s = \frac{120 \times 60}{6} = 1{,}200 \text{ rpm.}$$

For a 24 pole machine—

$$S_s = \frac{120 \times 60}{24} = 300 \text{ rpm.}$$

Where— S_s = Synchronous speed.

If the two leads to one phase of a two-phase winding are reversed, the relative polarities of the phase currents are reversed and the field will rotate in the opposite direction.

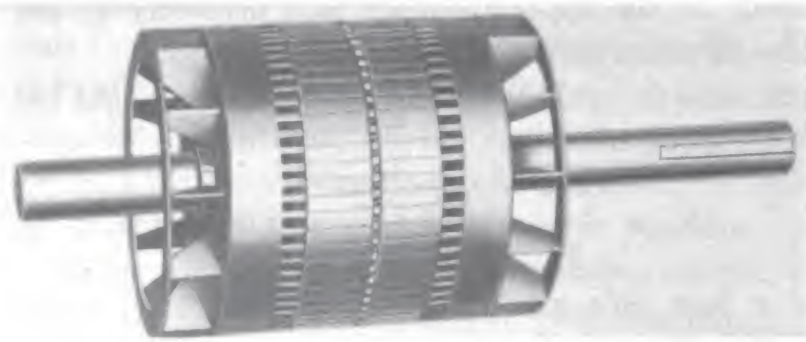
If a three-phase current is applied to a three-phase winding, a rotating field is produced as in the two-phase job. And it can be reversed by changing any two of the three line leads.

Now that you know how a rotating field is produced in the stator of a motor, the next thing is to find out how it produces torque. Put the field to work.

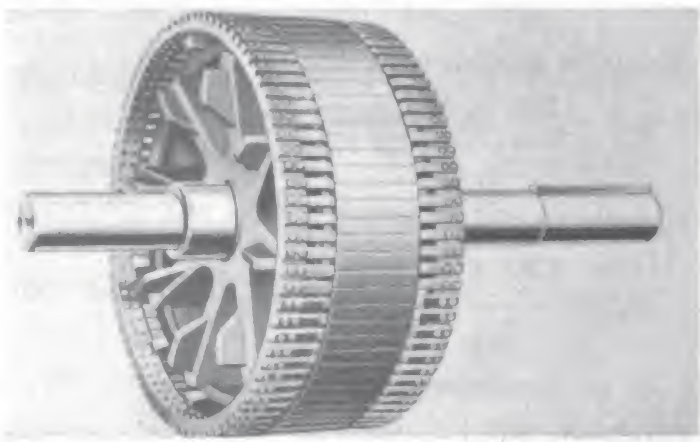
SQUIRREL CAGE ROTOR

The stator windings for the different types of three-phase motors may be identical. In fact, they are often interchangeable. The motors DIFFER in the CONSTRUCTION of THEIR ROTORS. Of the three principal types—SYNCHRONOUS, WOUND ROTOR, and SQUIRREL CAGE—the squirrel cage is the most widely used.

Figure 183 shows two squirrel cage rotors. The basic principles of construction are the same. Each is made of a laminated iron core mounted on a spider or frame work secured to the shaft. Bars of copper, aluminum, or some alloy which is a



A



B

Figure 183.—Squirrel cage rotors for a.c. induction motors.

good conductor are laid in slots of the core. These bars are welded to end rings at each end of the rotor. That's all there is to it—no electrical connections to outside lines, no insulation, no phases, and no slip rings.

Figure 183*B* shows a squirrel cage winding removed from the iron core. Somebody thought it resembled a squirrel cage, and that's where the motor got its name.

HOW IT WORKS

To get a start, look at figure 184. According to your hand rule for generators, if the magnetic field is moved in the direction shown, a voltage will be induced in the conductor. If the

ends of this conductor are shorted together, a current will flow in the direction marked. Now, you have a CURRENT-CARRYING CONDUCTOR IN A MAGNETIC FIELD. What is the result?

That's correct, MOTOR ACTION. Furthermore, by using your hand rule for motors, you find that the conductor moves in the SAME DIRECTION that the magnetic field is being moved.

In figure 184, the magnetic field is moved by moving the magnets. The same result would be obtained if ONLY THE MAGNETIC FIELD moved, as it does in the stator of a three-phase motor.

A SUMMARY

As the rotating field in the stator of the motor travels around the stator it cuts across the copper bars in the rotor. Thus a

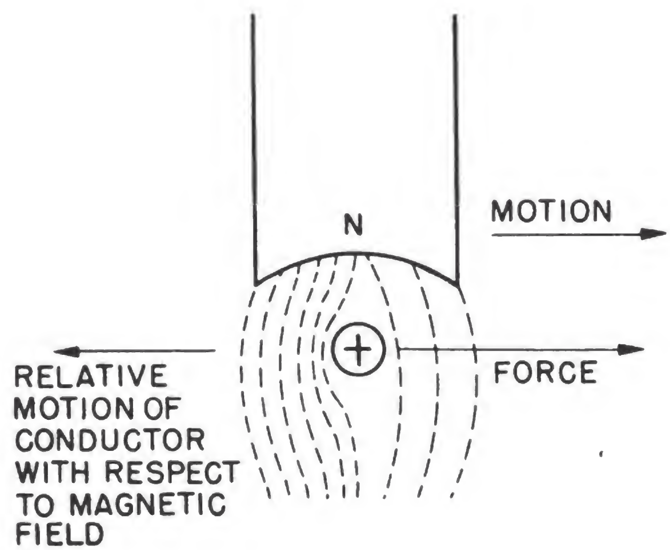


Figure 184.—Force on a conductor in a moving magnetic field.

voltage is induced in these bars and, since they are short-circuited, current flows in them. Again you have current-carrying conductors in a magnetic field. Result, motor action; and a torque is in the same direction as the rotating field, so the rotor of the motor begins to rotate in the same direction as the rotating field. To reverse the rotor, reverse the field by reversing two stator leads.

SLIP

As the rotor begins to turn, in the same direction as the rotating field, less RELATIVE MOTION exists between rotor and stator. The field doesn't pass the rotor bars as often as it did when the rotor was standing still, because the rotor is TURNING WITH the field.

What happens if the rotor reaches the same speed as the rotating field? Then there is NO RELATIVE MOTION between the field and rotor. If the field doesn't pass the rotor, NO FLUX LINES cut the bars. No voltage is induced in the rotor bars, so no currents flow in them, and consequently NO TORQUE is developed—the rotor begins to slow down. As it does, the bars are cut again by the rotating flux field and the torque is developed which keeps the rotor going.

However, you can see that it isn't possible for the rotor to attain the same speed as the rotating field. There must always be some DIFFERENCE between the SPEED OF THE ROTOR and the SPEED OF THE FIELD in order to induce a voltage in the rotor bars. And it should be apparent that the greater the difference, the greater the induced voltage in the rotor. This DIFFERENCE between the rotor speed and the synchronous speed is called SLIP.

Slip is expressed as a percentage of synchronous speed. Thus—

$$\text{Slip} = \frac{S_s - R_s}{S_s}$$

where—

S_s = Synchronous speed.
R_s = Rotor speed.

For example, a three phase, four pole, squirrel cage motor operating on a 60 cycle line at 1,728 rpm would have a slip of 4%. Here is how the problem is solved—

$$S_s = \frac{120f}{P} = \frac{120 \times 60}{4} = 1{,}800 \text{ rpm.}$$

$$\text{Slip} = \frac{S_s - R_s}{S_s} = \frac{1800 - 1728}{1800} = .04 \text{ or } 4\%$$

A CONSTANT SPEED?

Although induction motors are called constant speed motors, the speed is not absolutely constant. If the load on a motor is increased, the rotor current must increase in order to produce the additional torque required. In order for this additional current to flow through the rotor winding, the voltage must increase enough to offset the additional IR drop in the winding. To increase the inducted voltage, the slip must increase; the motor slows down as load is added.

The resistance of the squirrel cage winding is low, so that the increase in IR drop caused by the additional current is small compared to the TOTAL VOLTAGE, and the INCREASE in SLIPPAGE is correspondingly small. Thus, because motor speed decreases only slightly as the load increases, it is said to have GOOD SPEED REGULATION.

Another fact should become obvious. If the resistance of the squirrel cage winding is increased, any increase in load will cause a greater decrease in speed than if the rotor had a lower resistance. That is, high resistance squirrel cage rotors will have less speed regulation—slow down more with load—than low resistance rotors.

TORQUE

The torque delivered by an a. c. motor depends upon the field strength and rotor current just as in the d. c. motor. However, there is one additional factor which must be considered—the TRUE POWER delivered by an a.c. circuit depends upon the POWER FACTOR of the circuit. So, for an a. c. motor—

$$T = K\Phi I_R \cos\theta_R$$

where,

$K =$ a constant for any given motor.
$\Phi =$ Flux
$I_R =$ Rotor current.
$\cos\theta_R =$ Power factor of rotor circuit.

For further explanation of this condition, consider the two diagrams shown in figure 185. Figure 185*A* shows a cross section of an induction motor with a squirrel cage motor. The

magnetic field is rotating in a clockwise direction and the rotor is at a standstill. By applying the hand rule for generators, you will find that a voltage is being induced inward under the north pole and outward under the south pole.

The flux in the air gap is not uniform, but varies as a sine curve. It is more dense near the center of the pole and decreases toward the edges of the pole. Thus, the emf induced in the rotor bars varies as indicated by the size of the dots and crosses used to indicate the direction of the voltage.

The bars are short circuited, so a current flows. At standstill, the frequency of this rotor current is equal to the frequency of the stator current. The effective value of the rotor current I_R is—

$$I_R = \frac{E_R}{\sqrt{R_R^2 + X_R^2}}$$

Because the frequency of the rotor current is high at starting, the reactance of the rotor circuit is high as compared to the resistance. This causes the current to lap the voltage by a large angle. That means that maximum current flows in a conductor several degrees (angle θ) behind maximum voltage.

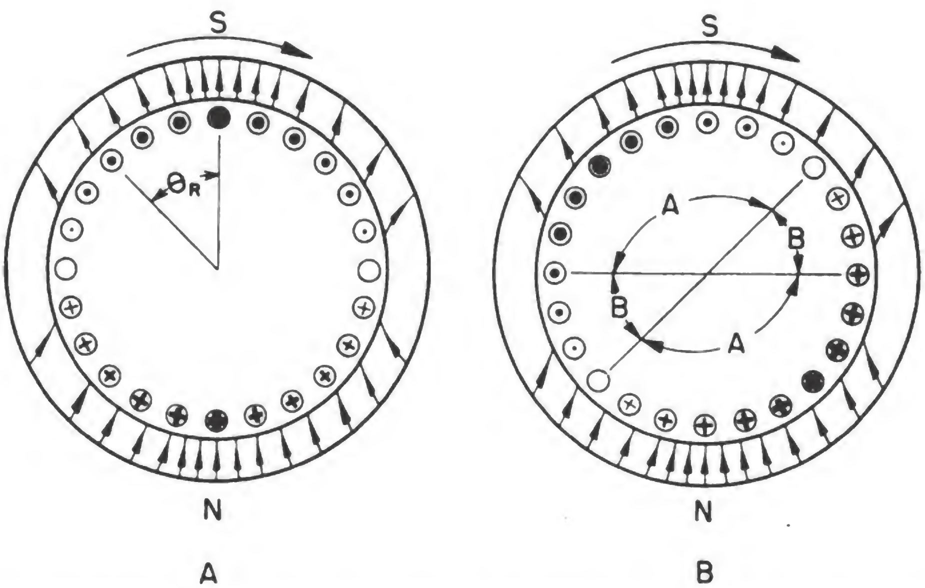


Figure 185.—Rotor current and voltage relationship in a squirrel cage rotor, and resultant torque.

Figures 185*A* and 185*B* show this condition. Figure 185*A* shows the voltage induced in a rotor at a given instant, and the

positions of the poles at this instant. Figure 185*B* shows the current at the same instant. You will note that the maximum current in a conductor is several degrees behind the maximum voltage. The current is lagging θ degrees behind the voltage.

The figure also shows field flux and rotor current relation. In figure 185*B* the rotor conductors within angle *A* produce a torque tending to turn the rotor in a clockwise direction, while the conductors within angle *B* produce a torque which tends to turn the rotor in a counterclockwise direction. It is apparent that the conductors within angle *A* produce the GREATER TORQUE and the rotor turns in a clockwise direction, the same direction as the rotating field.

You can see that if the angle between the current and voltage is reduced, the total torque will be increased; or if the angle is increased, the torque will be decreased. Thus, the torque developed by the motor depends upon the field flux, rotor current, and phase relation of the two. Mathematically—

$$T = K\Phi I_R Cos\ \theta_R$$

THE STARTING CURRENT IS HIGH

The high reactance of the rotor circuit at the time of starting gives the rotor current a low power factor. In fact, it is so low in an ordinary squirrel cage motor that to produce 150% of full load torque at starting requires four to nine times the full load current. That is, if the full load current of a certain squirrel cage motor is 60 amperes, the starting current will be between 240 and 540 amperes.

The motor acts like a transformer in which the stator winding is the primary and the rotor winding is the secondary. Hence, as the rotor current goes up the stator current increases. And a rotor current four to nine times the full load current means the current drawn from the line at starting is four to nine times the full load line current.

You don't need much imagination to visualize what would happen to a line if several large induction motors were thrown it at the same time, without some method for cutting down the excessive starting current. Starters for these motors will be discussed later.

Once the motor is started, the current begins to decrease. As the speed of the rotor increases, the frequency of the rotor current decreases—the rotating field sweeps across the rotor conductors less frequently. As the frequency of the current decreases, reactance decreases—$X_L = 2\pi fL$—and the power factor increases. As the power factor increases, it takes less current to produce the same power. The maximum power factor is obtained at full speed. This power factor runs around 70% for small motors but may go as high as 90% for very large motors.

HOW THE STARTING CURRENT CAN BE REDUCED

The starting current of the squirrel cage motor can be reduced by using a higher resistance rotor. That is, use smaller bars and increase the resistance of the end rings.

Suppose that X_R and R_R in figure 186*A* represents the resistance and reactance of the rotor of a squirrel cage motor at standstill. Then angle θ_R represents the phase angle between the rotor current and rotor voltage. If the resistance is increased to the value shown in figure 186*B* the reactance remains the same, and the phase angle θ_R is decreased. Thus, the power factor is increased and the starting current is reduced.

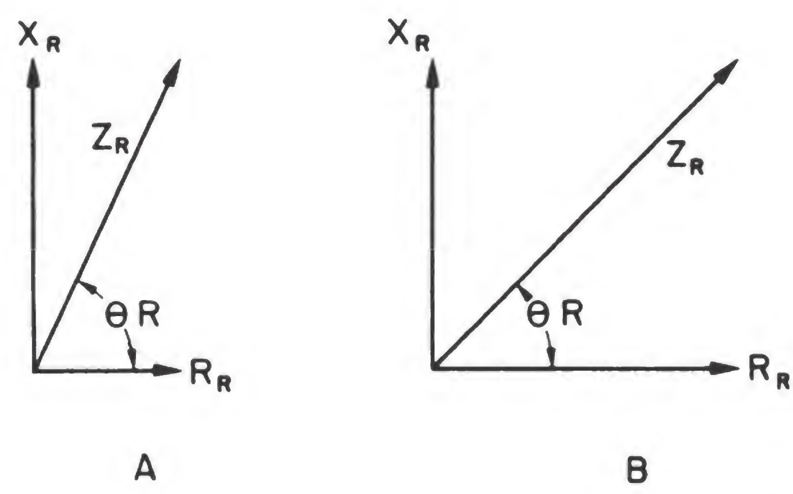


Figure 186.—Effect of high rotor current on power factor angle.

The maximum starting torque is obtained when X_R and R_R are equal at starting. Then the starting current is about three and one-half to four times the full load current.

However, remember that increased rotor resistance results in increased slip—lower motor speed—and greater speed variations with load changes. Thus, by varying the resistance of the rotor circuit, manufacturers obtain different starting and operating characteristics for induction motors.

In general the operating characteristics of squirrel cage motors may be compared to the operating characteristics of d.c. shunt motors.

WOUND ROTOR MOTORS

The undesirable features of a high resistance squirrel cage rotor may be eliminated by using a WOUND ROTOR. With the wound rotor, high resistance may be used for starting, and then cut out as the motor comes up to speed.

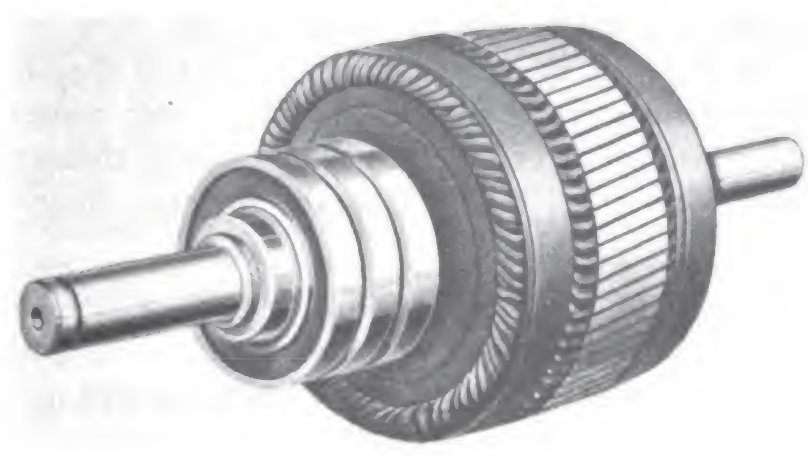


Figure 187.—Wound rotor for an induction motor.

Figure 187 shows the rotor of a wound rotor motor. Instead of using short-circuited bars, the rotor is wound with a three phase drum winding. The windings are connected star or delta and the three leads are brought out to three slip rings placed on the shaft. Brushes riding on these slip rings are

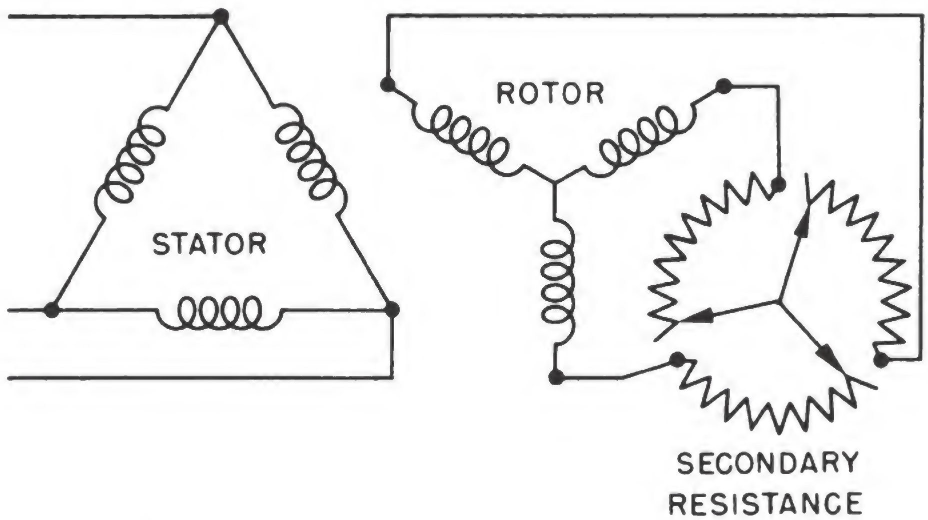


Figure 188.—Connections for a wound rotor motor.

connected to an external resistance through which the rotor circuit is completed. The stator winding is the same as for a squirrel cage motor.

Figure 188 is a schematic drawing of the rotor circuit and the external resistance of a wound rotor motor. By varying the external resistance, the resistance of the rotor circuit is varied. At starting, the resistance is inserted in the circuit to obtain maximum starting torque. As the motor comes up to speed the resistance is cut out until the running characteristics of the motor are about the same as the standard squirrel cage motor.

The wound rotor motor has the following advantages over the squirrel cage motor—

High starting torque with low starting current.

No abnormal heating during starting.

Good running characteristics.

Adjustable speed.

On the other hand, its initial and maintaining cost is higher, and the external resistance is bulky.

DOUBLE SQUIRREL CAGE MOTOR

Another type of squirrel cage motor which has good operating characteristics is the DOUBLE SQUIRREL CAGE. The rotor has

two squirrel cage windings placed as shown in figure 189. The bars of the inner winding have a low resistance and are surrounded by iron on all sides except the side next to the outer winding. Thus, it has a low resistance and high inductance.

The bars of the outer winding have a high resistance and are surrounded by iron on only two sides. Thus, the outer winding has a high resistance and low inductance as compared to the inner winding.

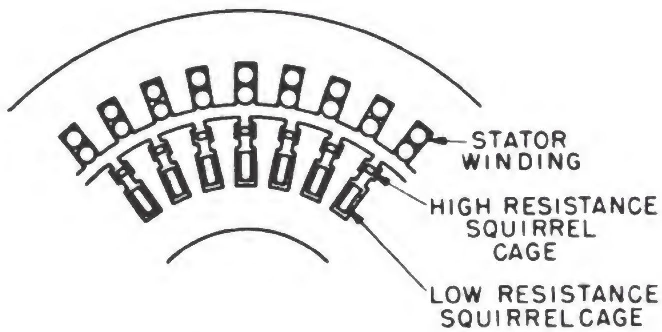


Figure 189.—Double squirrel cage rotor.

As the rotating field sweeps past, an emf is induced in each winding. But at starting, the rotor frequency is the same as the line. This high rotor frequency causes the reactance of the inner winding, which has high inductance, to be much higher than the reactance of the outer winding. The reactance is the greater part of the impedance of each winding. So, the impedance of the inner winding is higher than the impedance of the outer winding at starting. Naturally, more current flows in the high resistance outer winding at a high power factor. This gives the motor a good starting torque.

As the speed of the rotor increases, the frequency of the rotor currents decreases. The reactances of the windings go down. The impedance of each winding becomes more nearly the resistance of the winding. Finally, near synchronous speed, the resistances of the windings determine their relative impedance; the impedance of the low resistance winding is less than the impedance of the high resistance winding. As a result, the low resistance winding carries practically all the rotor current. and the motor runs as a standard squirrel cage motor.

ADJUSTING SPEED

The speed of the WOUND ROTOR MOTOR may be VARIED over a SMALL RANGE, but the speed of the standard SQUIRREL CAGE MOTOR is inherently CONSTANT. The speed of a squirrel cage motor varies directly with the frequency of the applied voltage and inversely as the number of pairs of poles. Generally it isn't practical to change frequencies. If motors are operated at LOWER FREQUENCIES than the one for which they are designed, they OVERHEAT and BECOME INEFFICIENT.

However, motors are designed with one or two stator windings whose number of poles can be changed by changing external connections of the windings. For example, a motor may be designed with a winding which may be connected for four or eight poles. On a 60 cycle line, the four pole connection would give a synchronous speed of 1,800 rpm, and the eight pole connection would give a synchronous speed of 900 rpm. The motor might have two special windings, each good for two speeds. If one winding is designed for four or eight poles and the other winding for six or twelve poles, the synchronous speeds obtainable would be 1,800, 1,200, 900, and 600 rpm.

SYNCHRONOUS MOTOR

You will recall that a d.c. generator can be operated as a d.c. motor. Just so, an a.c. generator can also be operated as an a.c. motor. When so used, its rotor runs at synchronous speed and it is called a SYNCHRONOUS MOTOR.

The stator of a synchronous motor is the same as the stator of squirrel cage motor—it is not an induction motor. The motor has a wound rotor and is excited by a d.c. current, thus setting up magnetic poles of FIXED POLARITY. These poles lock in step with the poles of the rotating field, and the rotor is pulled around by the rotating field. Naturally, the two fields, being locked together, cause the rotor to travel at the same speed as the rotating field; hence, the name synchronous motor.

Synchronous motors are generally of the salient pole type shown in figure 190*A*. Figure 190*B* shows the polyphase stator

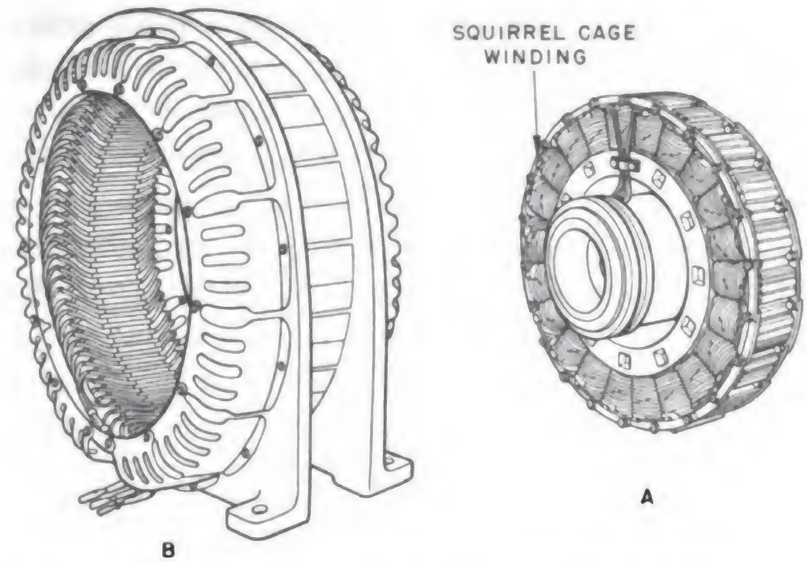


Figure 190.—Rotor and stator of a synchronous motor.

for the motor. When polyphase voltages are applied to the stator a rotating field is produced. When d.c. current is applied through the slip rings to the rotor windings, a fixed polarity is produced at each pole.

Suppose that the stator and rotor are energized at the same time. Figure 191 illustrates what would happen. Figure 191*A* shows the poles of the stator approaching rotor poles of opposite polarity. According to the laws of magnetism, the stator poles attract the unlike poles of the rotor. This attraction tends to rotate the rotor in a direction opposite to that of the rotating field.

But just as the rotor is ready to start, the stator poles have passed and are on the other side attracting the rotor poles in the opposite direction, as shown in figure 191*B*. The same

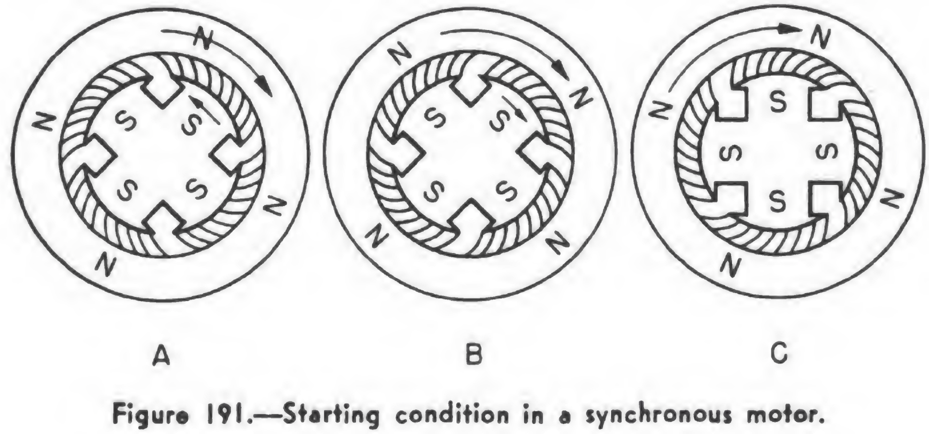


Figure 191.—Starting condition in a synchronous motor.

things happen when the stator poles pass rotor poles of the same polarity. The rotor poles are repelled in first one direction, then the other. The average torque is zero. Thus a synchronous motor in its pure form has no starting torque.

If the motor is a four pole job on a 60 cycle line, the synchronous speed of the field is 1,800 rpm as soon as the field is excited; but the rotor just won't go from a standstill to 1,800 rpm in "nothing flat". What will happen is that the windings will be yanked out of their slots and the whole motor wrecked. However, if the rotor is brought up to a speed equal or approximately equal to the speed of the rotating field, it will lock in step with the rotating field and be pulled around by it, at synchronous speed.

STARTING SYNCHRONOUS MOTORS

Generally, synchronous motors are started as squirrel cage motors. A squirrel cage winding is placed upon the rotor as shown in figure 192. To start the motor, the d.c. field on the rotor is de-energized and the stator is energized. Thus, the motor starts as a squirrel cage induction motor. When the motor comes up to speed—slightly less than synchronous speed—the d.c. field on the rotor is excited. The rotor locks in step with the rotating field, and is pulled around at synchronous speed.

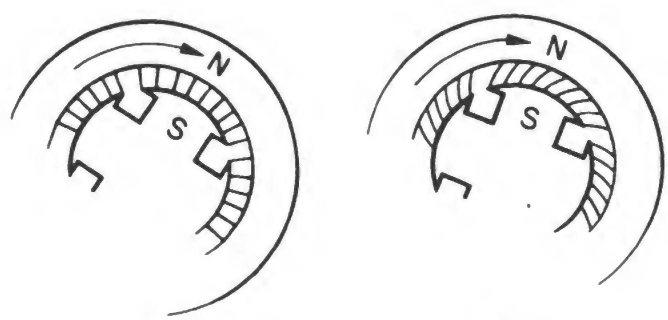


Figure 192.—Effect of magnetic coupling.

SYNCHRONOUS CONDENSERS

A synchronous motor may be used to improve the power factor of an a.c. line. When so used it is called a SYNCHRONOUS CONDENSER.

By changing the excitation of the d.c. field of the synchronous motor, its power factor may be varied from a LOW LAGGING POWER FACTOR to a LOW LEADING POWER FACTOR. If the d.c. field is under-excited, the motor has a lagging power factor. If it is over-excited, it produces a leading power factor. Thus, the power factor characteristics of the synchronous motor are under the control of the operator at all times.

When used as a synchronous condenser, the motor is connected on the line IN PARALLEL with the other motors on the line, and run without load or with a very light load. The field of the synchronous motor is over-excited just enough to produce enough leading current to offset the lagging current of the line and produce unity power factor.

The synchronous motor can be made to produce up to 80 percent leading power factor. But of course leading power factor on the line is just as bad as a lagging power factor, so the synchronous motor is regulated to produce just enough leading current to offset the lagging current.

DON'T FORGET THE SWITCH

Regardless of how the synchronous motor is used, don't forget the FIELD DISCHARGE SWITCH. It is just as important as it is on the generator. When the stator is energized while the rotor is at standstill, the rotating field sweeps past the d.c. winding at a rapid rate. There are many turns in the d.c. windings and a very high voltage is induced in them. Unless there is a field discharge switch, the insulation will be punctured.

SINGLE PHASE MOTORS

If one lead to a three-phase induction motor is disconnected while the motor is running, it will continue to run on one phase. However, it will overheat if rated load is still carried. If the motor is stopped, it will not start again with the one lead disconnected. And thereby hangs a tale. Single phase induction motors will run when once started, but they won't start themselves.

When the single-phase winding is excited with a single-phase current, a pulsating field is produced in the stator. The magnetic field changes in all the poles at exactly the same time and same rate, so no rotating field is produced. A voltage is induced in the squirrel cage rotor—transformer action—but no torque is produced. The motor is merely acting as a transformer—the stator is the primary and the rotor is the secondary. The current flowing in the rotor conductors, due to transformer action, produces a flux which opposes the flux in the stator just as the ampere-turns of the secondary of a static transformer oppose the primary ampere-turns.

The condition which exists is shown diagrammatically in figure 193*A*. Suppose you take an instant when an increasing current is flowing from L_1 to L_2. An expanding flux is established which INDUCES AN EMF in the rotor bars, causing current to flow as indicated. This rotor current will set up poles at N_r and S_r in DIRECT LINE with the stator poles N_s and S_s. Thus no torque is developed because of the relative position of

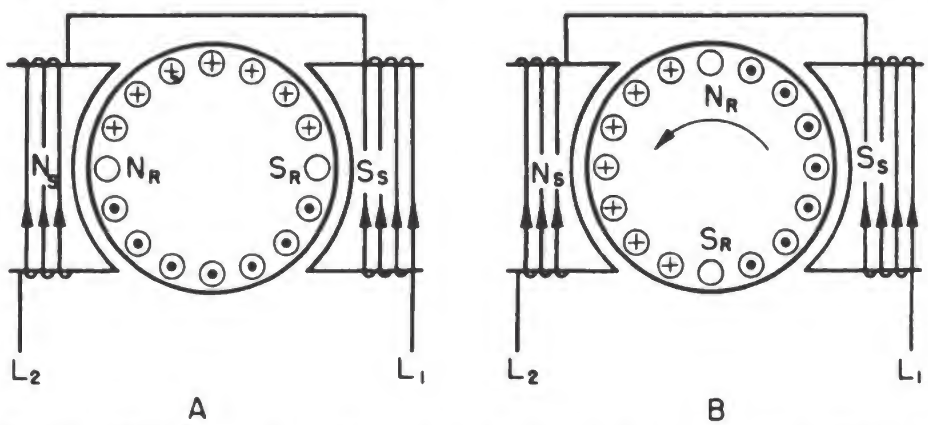


Figure 193.—Rotor currents in a single phase motor at standstill and when rotating.

the stator and rotor poles. Other instants during the cycle of current will produce the same result, so no torque is produced by the single phase motor and it is not self-starting.

Suppose the rotor is turned by some means in a clockwise direction. The rotor conductor will cut across the flux established by the stator winding. As a result, an emf will be induced in the rotor conductor. This SPEED EMF, as it is called, will cause a current to flow as indicated in figure 193*B*. The field set up by this current is at right angles to the main field.

Because of the high reactance of the rotor circuit, this current will lag the speed emf by approximately 90°. So the field developed by the speed current is at right angles to the main field and differs in time phase by approximately 90°. Thus a rotating field is established and the motor continues to run, once it is started.

Since single phase motors aren't self-starting, some auxiliary means must be used to start them. Of course, you could start the very small ones by hand. However, this doesn't solve the problem of starting the larger motors and it is rather an inconvenient method of starting the small ones. So, some other method is desirable.

One method is to SPLIT the phase by combinations of INDUCTANCE, CAPACITANCE, and RESISTANCE.

SPLIT PHASE MOTOR

Figure 194 shows a common method of splitting the phase. Two windings—a main winding and a starter winding—are placed in the stator as shown in figure 195. The main winding is wound on the stator and the starting winding is wound on top of it in such a manner that the centers of the poles of the two windings are displaced by 90°.

The windings are shown schematically in figure 194. They are connected in parallel to the same supply voltage; therefore

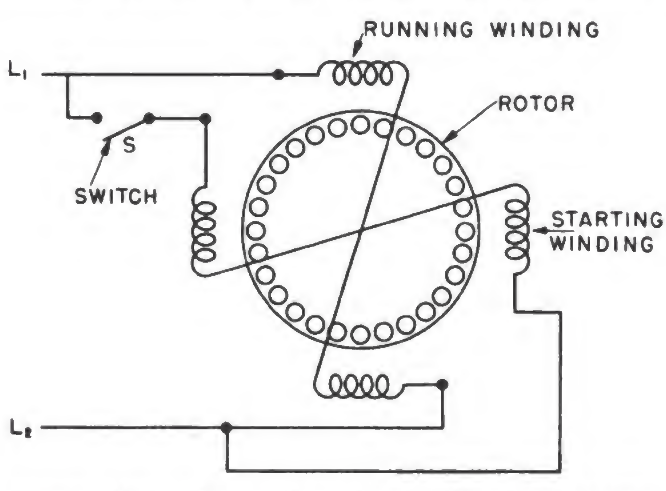


Figure 194.—Connections for a split phase motor.

the same voltage is applied to both windings. But—and here's the secret to the operation of the split phase motor—the currents in the two windings aren't in phase.

The main winding has a LOW RESISTANCE and, being surrounded by iron on all sides except one, it also has a HIGH INDUCTANCE. On the other hand, the starting winding is wound with SMALLER WIRE and has a HIGH RESISTANCE. Also, it has iron on only two sides, and consequently has LESS INDUCTANCE than the main winding. Therefore, when the same voltage is applied to both windings, the current in the main winding is going to lag the voltage more than does the current in the starting winding.

Now suppose the current in the main winding lags the voltage by 50° and the current in the starting winding lags the voltage by 30°. The magnetic fields set up by the currents are 90° apart, since the windings are displaced 90°—and the two windings have a current phase difference of 20°. This produces a weak rotating field which starts the motor. You can readily see that this field isn't going to be as strong as the rotating field produced by a regular two-phase current in which the phase difference is 90°; but it will start the motor. A Model-T won't produce as much power as a Lincoln, but if you have a Model-T and don't have a Lincoln, you'll manage to get around in the Model-T.

When the motor comes up to speed, a centrifugal device *A* (figure 195) opens a switch *B* in figure 195 and disconnects the starting winding from the line.

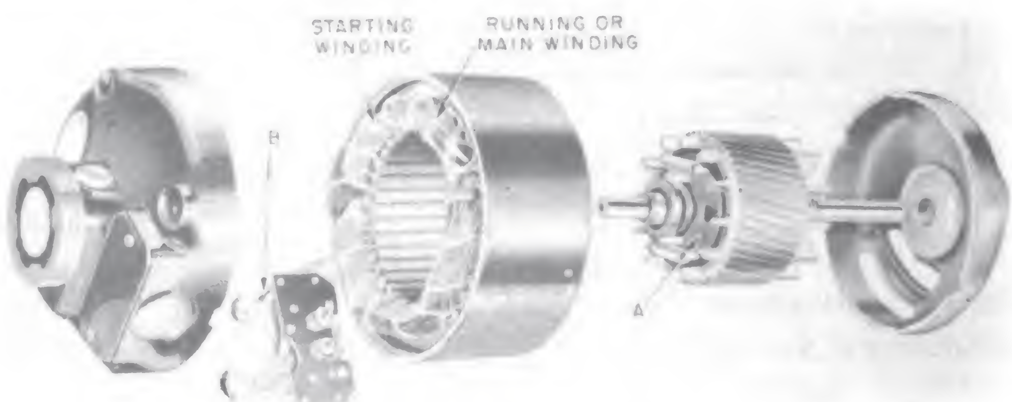


Figure 195.—Exploded view of a split phase motor.

The starting winding has a high resistance, and the I^2R loss is high. So, if the centrifugal device should fail to open the switch, the motor will run hot; and if it is allowed to run very

long with the starting winding in the circuit, the winding will be burned out. This is probably the most frequent cause for failure of split-phase motors.

The squirrel-cage rotor shown in figure 195 is typical of the type used in single-phase induction motors. The rotor winding is cast in one piece.

CAPACITOR MOTOR

Figure 196*A* shows a diagram of a single-phase induction motor in which capacitance rather than resistance is used to split the phase. A capacitor placed in the starting winding

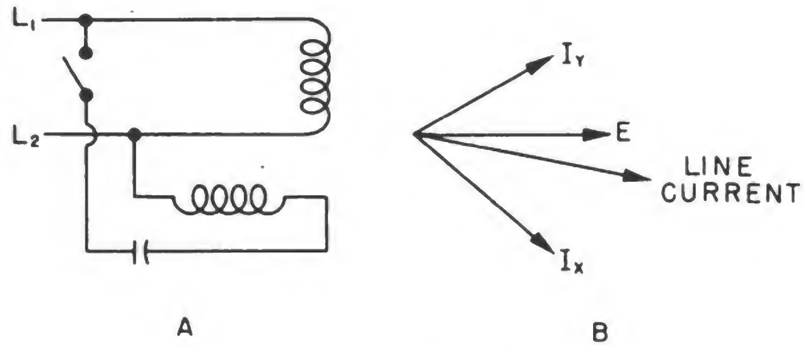


Figure 196.—Capacitor start motor.

circuit causes the current to lead the voltage in the starting winding circuit. By using the proper capacitor, the currents in the two windings—starting and running—can be made to differ in phase by approximately 90°. Then, you have a motor with approximately the same starting torque as a regular two-phase machine.

Figure 196 *B* shows the vector diagram for the currents in the two windings of a capacitor motor. In phase X—the running winding—the current I_x lags the voltage by approximately 45°. The current I_y in phase Y—starting winding—leads the voltage by approximately 45°. Thus, the two currents differ in phase by approximately 90°.

The two windings are displaced by 90°, as shown in figure 195. With the 90° phase difference of the two currents, the starting torque produced is equivalent to the starting torque of a two-phase motor. Furthermore, the resultant line current is

almost in phase with the line voltage which gives the motor an exceptionally high power factor—almost unity.

Where a starting winding is used only to start the motor, it is disconnected from the current by a centrifugal device when the motor gets up to speed. This motor is called a CAPACITOR-START, INDUCTION-RUN MOTOR. However, recent improvements of capacitors, and reduction in their cost, have made it practical to build motors in which the starting winding in series with a capacitor is left across the line. Thus a motor operates from a single-phase line with the characteristics of a two-phase motor.

A condenser which is large enough to supply the current for a high starting torque is too large for the normal load while running. So, two condensers are used for starting and one is cut out when the motor reaches normal speed.

Figure 197*A* shows how the two capacitors are connected in parallel to take care of the high starting current—both are in

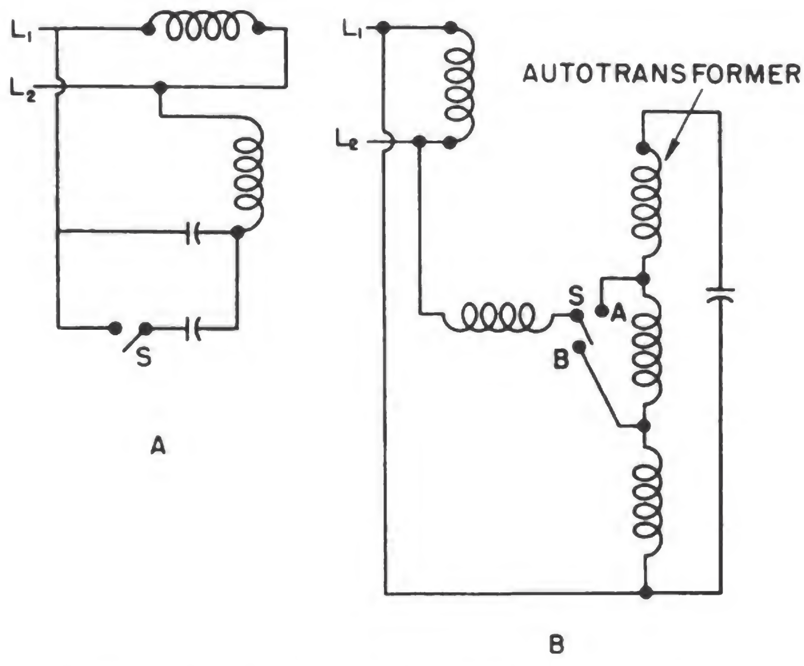


Figure 197.—Connections for single phase motors.

series with the starting winding. When the motor comes up to speed, a centrifugal device cuts the larger capacitor out of the circuit, and the motor continues to operate with the small condensers in the starting circuit.

Another scheme which permits the starting circuit to draw a large leading current with a comparatively small condenser in the circuit is shown in figure 197*B*.

When the motor starts, switch *S* connects phase *Y* to point on *A* on the autotransformer. This puts a high voltage—generally about 600 volts—across the condenser. It can stand this high voltage for the short starting period, but not continuously.

During the starting period, the high transformer ratio provides a very high current—about 20 times as high as would flow if the condenser were connected directly in phase *Y*—to flow in phase *Y*. This gives the motor a high starting torque.

When the motor reaches operating speed, the centrifugal device connects phase *Y* to point *B* on the transformer. This cuts the transformer ratio to about 1:2, and the current is about twice what would flow if the condenser were connected directly in phase *Y*. The motor has very good starting and running torque.

To REVERSE any of the above split phase motors, reverse EITHER the STARTING WINDING or RUNNING WINDING leads.

SHADED POLE MOTOR

Figure 198 is a partial diagram of a SHADED POLE MOTOR. Its stator winding differs from the other single phase motors

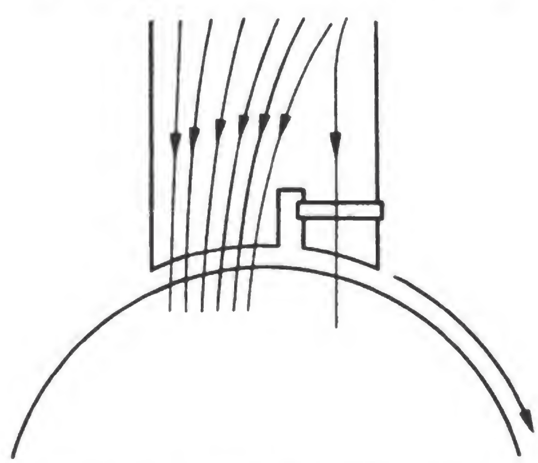


Figure 198.—Shaded pole motor.

in that it has definitely projecting field poles. They resemble the poles of a d.c. motor, except that the MAGNETIC CIRCUIT IS LAMINATED.

A low resistance, short circuited coil or copper band is placed across one tip of each small pole. And from that, the motor gets its name—shaded pole. The rotor of this motor is the squirrel cage type.

As the current increases in the stator winding, the flux increases. A portion of this flux cuts the low resistance shading coil. This INDUCES a CURRENT in the copper coil, and, by Lenz's Law, the current sets up a flux which opposes the flux inducing the current. Hence, most of the flux passes through the unshaded portion of the poles, as shown in figure 198.

When the current in the winding and the main flux reaches a maximum, the rate of change is zero, so no emf is induced in the SHADING COIL. A little later, the shading coil current, which lags the induced emf, reaches zero—and there is no opposing flux. So the main field flux passes through the shaded portion of the field pole.

The main field flux, which is now decreasing, induces a current in the shading coil. By Lenz's Law, this current sets up a flux which opposes the decrease of the main field flux in the shaded portion of the pole. As a result, the flux in the shaded part of the pole reaches its minimum value after the main field flux reaches its minimum value in the unshaded part of the pole.

Thus, the shading coil in effect RETARDS, in time phase, the portion of the flux which passes through the SHADED PART of the POLE. This lag in time phase of the flux in the shaded tip causes the flux to produce the EFFECT OF SWEEPING ACROSS the face of the POLE, from LEFT to RIGHT in the direction of the shaded tip. This behaves like a very weak ROTATING MAGNETIC FIELD and sufficient torque is produced to start a small motor.

The starting torque of the shaded pole motor is exceedingly weak, and the power factor is low. Consequently, it is built in small sizes suitable for driving small devices, such as small fans and relays.

REPULSION MOTORS

Single-phase motors may be repulsion starting. In this case, the rotor has a DRUM WOUND ARMATURE, a commutator, and

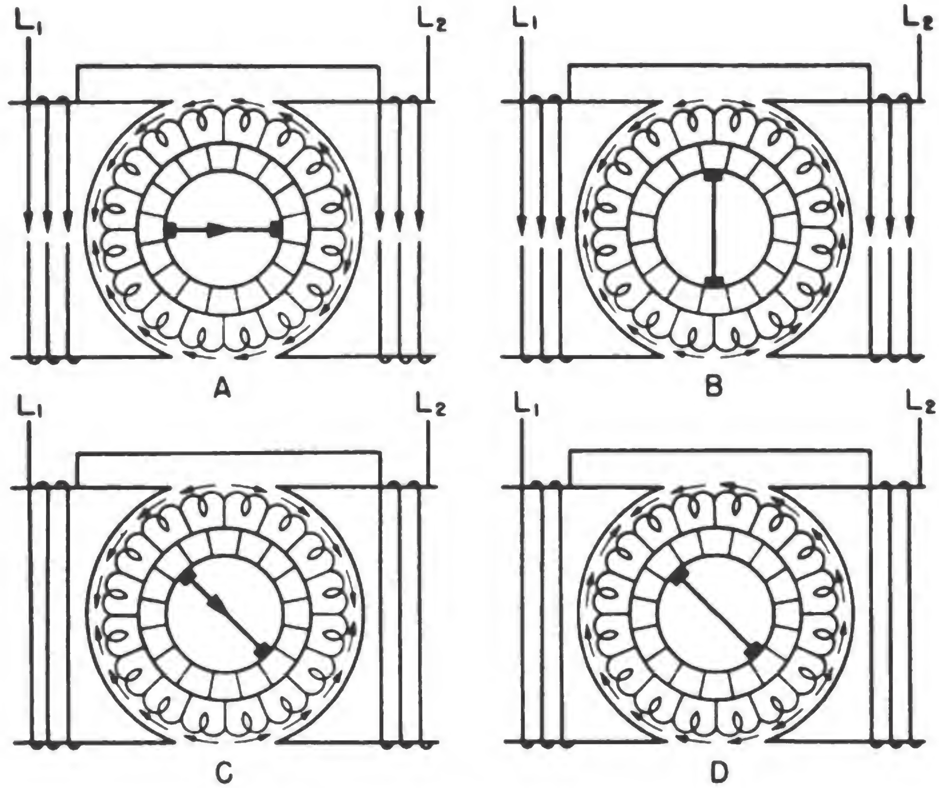


Figure 199.—Flow of current in a repulsion motor.

brushes. However, the brushes are not connected to the supply line. Instead, they are SHORT CIRCUITED.

The principle involved in repulsion starting is illustrated by the diagrams in figure 199. The current through the stator winding is alternating. However, its direction during a half cycle may be indicated as shown by the arrows.

Suppose, in diagram 199*A*, the current in the stator winding is increasing in the direction shown. The flux produced will induce voltage in the armature conductors as shown—prove it by hand rule. These voltages are in the SAME DIRECTION in all the conductors on each side of the brushes.

From the diagram 199*A*, you can see these add together to send a high current through the short-circuiting brushes and the windings. But half of the conductors under each pole are carrying current in one direction and the other half are carrying current in the opposite direction. Consequently, no torque is developed when the brushes are in this position—PARALLEL WITH THE MAIN FIELD.

If the brushes are SHIFTED 90° to the position shown in diagram 199*B*, the INDUCED VOLTAGES of each path NEUTRALIZE EACH OTHER—on each side of the brushes, half the voltages are in one direction and the other half are in the opposite direction. No voltage exists at the brushes and no current flows. Of course no torque is developed.

If the brushes are shifted 45° as shown in figure 199*C*, voltages are induced. The directions of the voltages are the same as in the other brush position. But you will notice that most of the conductors on each side of the brushes have voltages in the SAME DIRECTION. As a result, current will flow in the conductors as shown in 199*D*. Now all the conductors under one pole are carrying current in one direction and all the conductors under the other pole are carrying current in the opposite direction—just like a d.c. motor. A torque is developed and the motor runs.

To reverse the motor, shift the brushes back to the neutral plane—parallel with main field—and then shift them in the opposite direction.

By VARYING the DISTANCE the brushes are shifted from the neutral plane, the TORQUE of the motor is VARIED, and consequently speed is varied at a given load. Maximum torque and maximum speed are obtained when the brushes are shifted 15 to 20 degrees from the neutral plane.

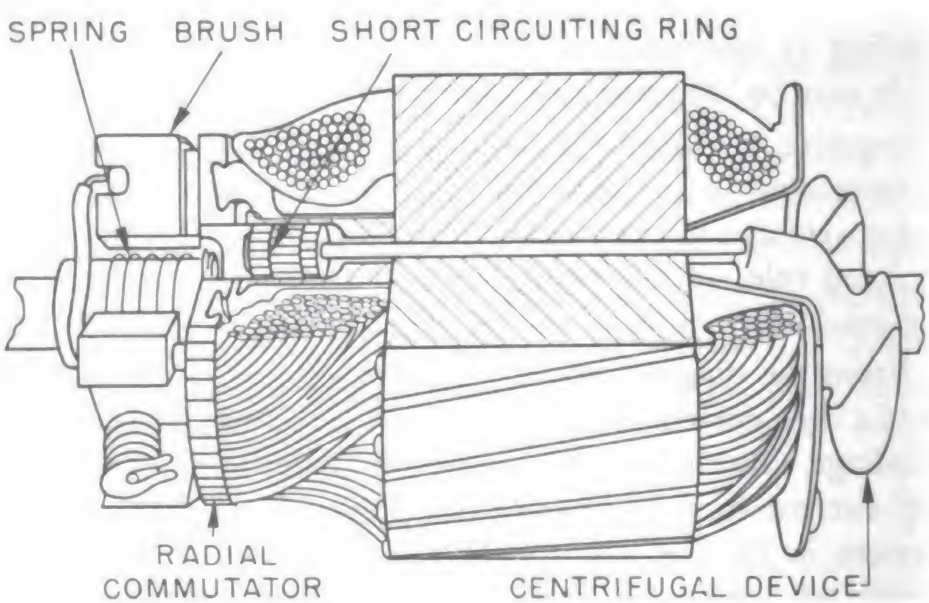


Figure 200.—Rotor of a repulsion motor.

The armature used with this motor may have a radial type commutator as shown in figure 200, or it may have the conventional cylindrical type of the d.c. machine. The brushes are mounted on a rocker ring which rotates to shift the position of the brushes.

The motor may be the REPULSION-START—INDUCTION-RUN type. If so, when the motor reaches a predetermined speed, the commutator bars are short-circuited and the motor operates as an induction motor. At the same time, the brushes may be lifted from the commutator.

When the motor reaches the predetermined speed, a centrifugal device (figure 200) exerts a pressure on some rods. These rods in turn lift a short-circuiting device, called a NECKLACE, into contact with the inner surface of the commutator and at the same time lift the brushes from the face of the commutator. The necklace SHORT CIRCUITS the commutator, and the motor runs as an induction motor.

These motors have a high starting torque at low starting current.

Another type is the REPULSION-INDUCTION MOTOR. This motor has the regular armature winding, commutator, and short-circuiting brushes, and in addition it has a squirrel cage winding. The repulsion winding gives it a high starting torque and the squirrel cage winding gives the motor the constant speed characteristics of the regular squirrel cage motor.

All the repulsion type motors are reversed by shifting the brushes.

SERIES MOTOR

If the armature and field currents in a d.c. motor are reversed at the same time, the direction of rotation isn't changed. Therefore, if such a motor is supplied with alternating current, the net torque will be in one direction. So fundamentally, the series motor could operate on EITHER d.c. or a.c. However, the ordinary d.c. series motor does not operate satisfactorily on a.c.

For one thing, the alternating current sets up LARGE EDDY CURRENTS in the solid parts of the field structure, such as the

yoke and core. These eddy currents cause excessive heating and lower the efficiency. This difficulty is reduced to a point where satisfactory operation is obtained BY LAMINATING the FIELD STRUCTURE. However, there are still iron losses with a.c. which do not occur with d.c.

Another reason why the ordinary d.c. series motor doesn't operate satisfactorily on a.c. is the HIGH REACTANCE of the field. This reduces the power factor and the output of the motor to such low values that its use on a.c. is impractical. To reduce this field reactance, the NUMBER OF TURNS in the field winding is REDUCED. And on a fractional horsepower a.c. series motor, this method cuts the reactance down to a point where satisfactory operation may be obtained on a 60 cycle line. But for large motors, 60 cycles is much too high, so lower frequencies—15 and 25—are used. These lower frequencies require larger and heavier transformers. Furthermore, low frequencies aren't always available. So most of the a.c. motors are fractional horsepower sizes.

When the number of turns in the field winding is reduced, the ampere-turns are reduced. To obtain maximum effect from the reduced value of flux, the reluctance of the magnetic circuit must be reduced to a minimum and the air gap must be very short. To reduce the reluctance of the magnetic circuit, high permeability iron is used at low flux densities.

Too offset the loss in flux caused by decreasing the ampere-turns of the field, the number of armature conductors is increased. Thus the a.c. series motor armature is larger than the armature of the ordinary d.c. series motor.

The stronger armature flux and weaker field flux result in more armature reaction. To offset this increased armature reaction, a compensation winding is usually imbedded in the face of the pole pieces. It may be connected in series with the armature, or it may be a short-circuited winding. In the latter case, the winding is an inductive winding—it is the secondary of a transformer of which the primary is the armature of the motor. By the compensating winding, either type, the armature reaction is reduced to a small value.

An additional commutating difficulty is encountered when a series motor is operated on a.c. When the brushes are placed

in the neutral plane, they short-circuit coils which are perpendicular to the main field. Thus the coils become the short-circuited secondary of a transformer with the main field poles the primary. The impedance of the short-circuited coil is low, so a very high current will flow in the coil. And from what you remember about d.c. commutation, you know sparks are going to fly.

This difficulty is overcome by connecting the coils to the commutator segments through resistances as shown in figure 201.

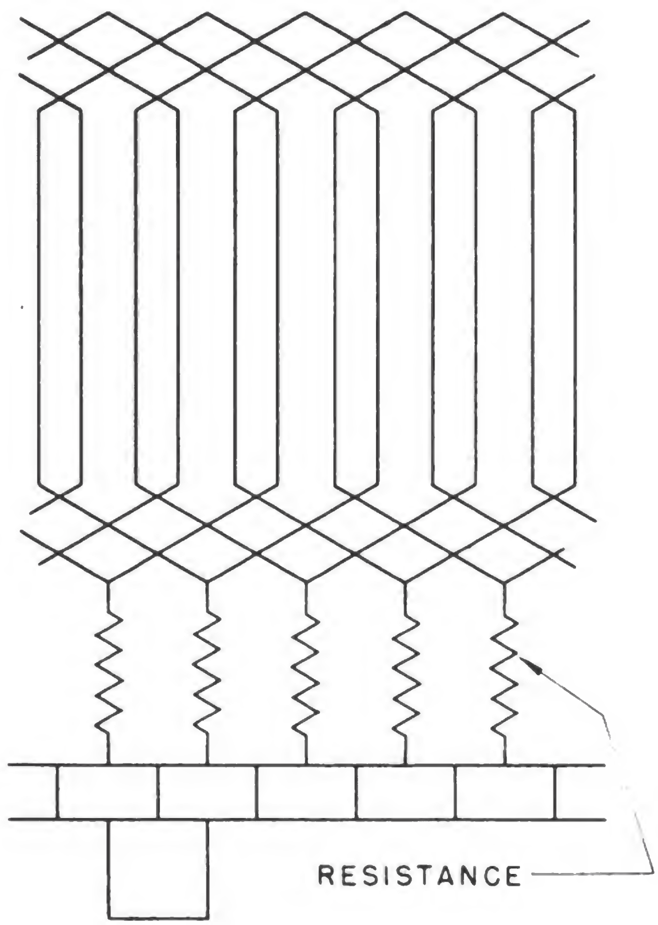


Figure 201.—Armature coils connected through resistances to segment.

You will notice that when the coils are short-circuited by the brushes, two resistors are in series with the coils. The impedance is increased enough to limit the short-circuit current to a low value. However, you will notice that the resistors are in parallel with regard to the line current. Two equal resistors in parallel have half the resistance of one of the resistors. And the two resistors in series have twice the resistance of one.

Thus, the resistance to the short-circuit current is four times as great as the resistance to the line current.

In order to improve commutation still further, the voltage between commutator bars is kept down by connecting only a single turn between the bars. Hence, a large number of segments and a large commutator are necessary.

UNIVERSAL MOTORS

The a.c. series motor has the same general characteristics as the ordinary d.c. series motor. By a careful compromise of design features, a series motor may be built to operate on both a.c. and d.c. circuits of the same voltage. Such motors are almost always in small sizes and are called UNIVERSAL MOTORS.

CHAPTER 21

A.C. CONTROLLERS

WHY ARE THEY NECESSARY?

When an induction motor starts up, there is a high inrush current—the larger the motor, the higher the current. This high starting current won't damage the motor, but it may cause considerable disturbance on the line. In some installations, the high starting torque may cause damage to the driven machinery, but that isn't generally true.

So, which induction motors must have a controller? The answer is—only the larger motors. Small induction motors—up to seven horsepower—are generally started by simply closing a switch directly across the line.

But large induction motors are not started in the same way. To protect the line from damage, the high, inrush current during the starting period is cut down by REDUCING the APPLIED VOLTAGE. When the voltage applied to the windings of the motor is reduced, the current is reduced also. Since the torque of an induction motor decreases as the square of the decrease in the applied voltage, REDUCED VOLTAGE STARTING isn't used unless it is necessary to protect the lines.

WAYS OF REDUCING APPLIED VOLTAGE WHILE STARTING

PRIMARY RESISTANCE starters accomplish voltage reduction across the stator windings by INSERTING RESISTANCE in the stator circuit at starting and cutting them out as the motor comes up to speed.

Another method of reducing the starting voltage is to use AUTO TRANSFORMERS. The primaries of the auto transformers are connected to the supply line, and the motor is connected to low voltage taps on the transformer until the motor comes up to a predetermined speed. Then the auto transformers are disconnected from the motor and the line, and the motor is connected directly to the line.

The RESISTANCE METHOD has the advantage of SMOOTH ACCELERATION, and it is cut out without ever disconnecting the motor from the line. With auto transformers the motor is momentarily disconnected from the line, and the LINE CURRENT is approximately HALF of the MOTOR CURRENT. However, with the RESISTANCE starter, the LINE CURRENT is EQUAL to the COIL CURRENT of the motor. Since the purpose of the starter is to protect the line from excessive starting currents, the auto transformer starter is generally used.

CONTROLLERS

The controllers, whether across-the-line or voltage reducing starters, may be manually operated or magnetically controlled. All of them have overload protection devices, and most of them give low voltage protection or low voltage release protection. Many controllers are designed to withstand high shock and are equipped with manual latches or automatic latching relays to prevent false operation. They are enclosed in a drip proof or watertight case.

Some typical a.c. controllers and their wiring diagrams are shown in this chapter. A thorough knowledge of their circuits and operating characteristics will help you to understand the a.c. controllers used by the Navy. The main thing to remember when installing, operating, or repairing controllers is to follow the diagrams and instructions provided by the manufacturer.

ACROSS-THE-LINE STARTER

Figure 202 shows a typical manual across-the-line starter. The line leads are connected to terminals L_1, L_2, and L_3, and the motor leads are connected to terminals T_1, T_2, and T_3. When

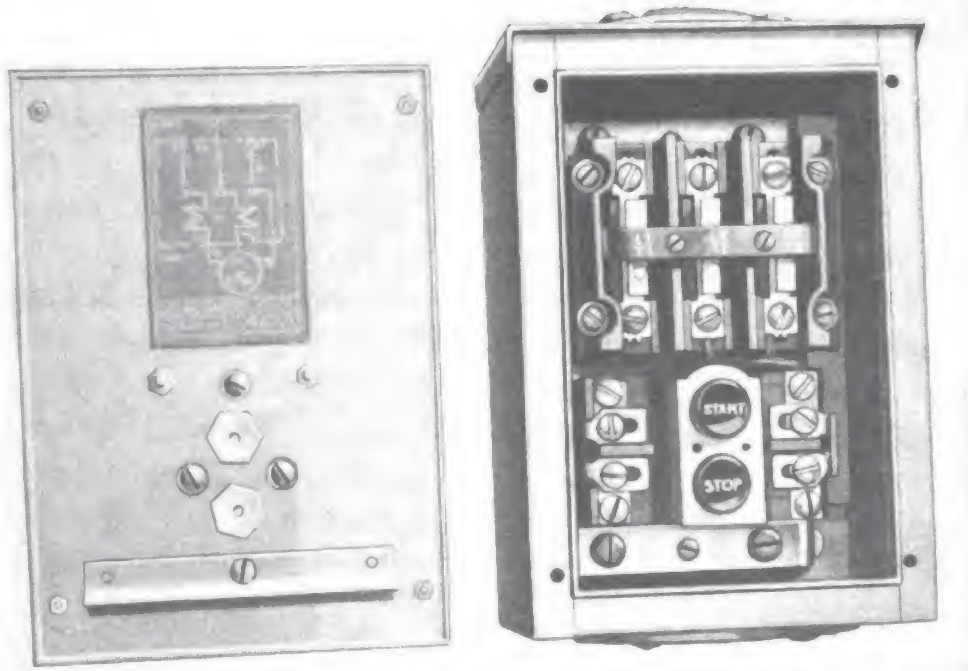


Figure 202.—Manually operated across-line starter.

the START button is depressed, a toggle mechanism operates the contact block, closing the main contacts. This completes the circuit from L_1, L_2, and L_3 to T_1, T_2, and T_3 respectively, and the motor is directly across the line. When the STOP button is depressed, the toggle mechanism opens the main contacts.

There are two thermal type OVERLOAD RELAYS which protect the motor against overloads. The relays are set to operate after the overload has existed for a predetermined time. The time is in INVERSE PROPORTION to the degree of overload. Of course the relays open when the motor is stopped. In this particular starter, the relays are reset when the start button is depressed again. Emergency run is obtained by holding down the starter button.

Figure 203*A* is a simplified diagram of the wiring and connections for use with a three phase motor, and figure 203*B*

shows the connections for a single phase motor. Notice that only one overload relay is necessary when the starter is used with a single phase motor.

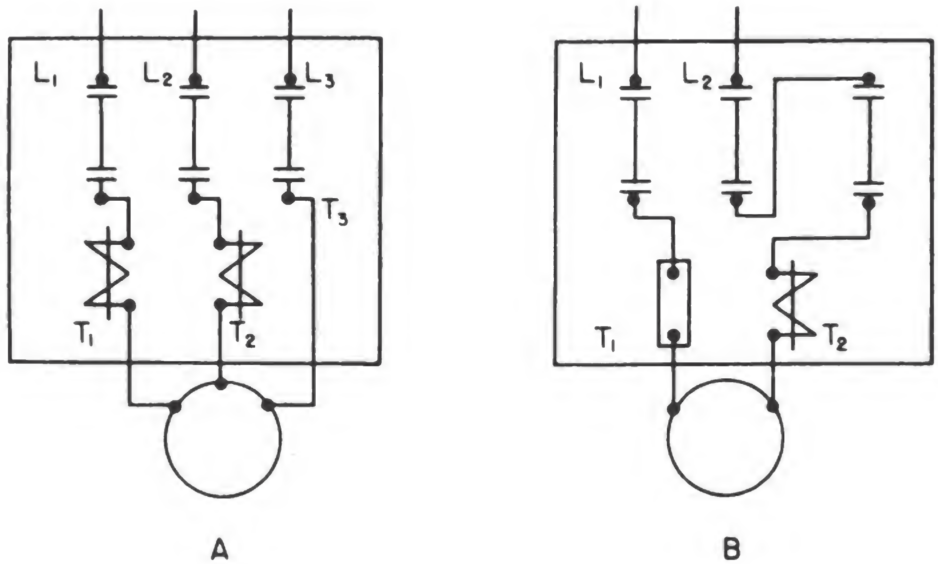


Figure 203.—Wiring diagram of across-the-line manual starter for three phase and single phase motors.

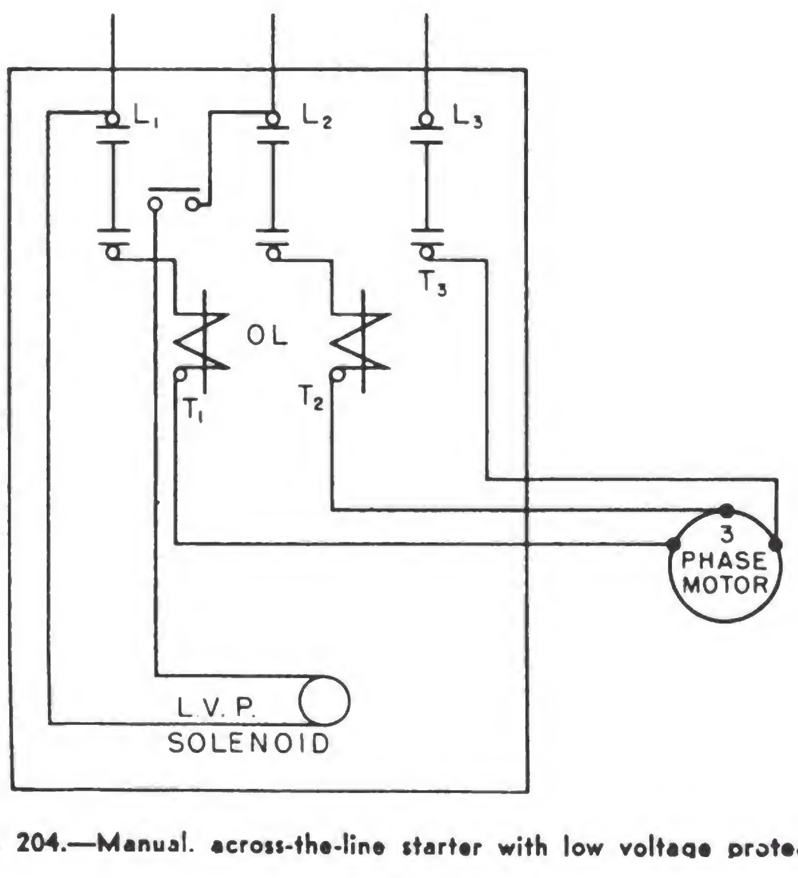


Figure 204.—Manual, across-the-line starter with low voltage protection.

Figure 204 shows the same starter that is shown in figure 202, except that a LOW VOLTAGE PROTECTION solenoid has been added. The solenoid is mounted below the starter mechanism. It is energized when the start button is depressed, and it operates to hold the main contacts closed after they have been closed by manually depressing the start button. If the voltage fails or falls below a predetermined value, the solenoid releases the toggle mechanism and the main contacts open.

Figure 204 shows the wiring diagram for this manually operated across-the-line starter with low voltage protection. The contact which completes the circuit through the solenoid is mechanically interlocked to the toggle mechanism which operates the main contacts.

An elementary wiring diagram for a manual across-the-line starter for a two-speed, two-winding motor is shown in figure 205. The motor is started on the high speed winding by depressing the FAST button which connects the motor directly across the line. Or it may be started on the low speed winding by depressing the SLOW button, which connects the slow speed winding directly across the line. The mechanical interlock, shown at *A* in figure 205*A*, prevents both windings being energized at the same time.

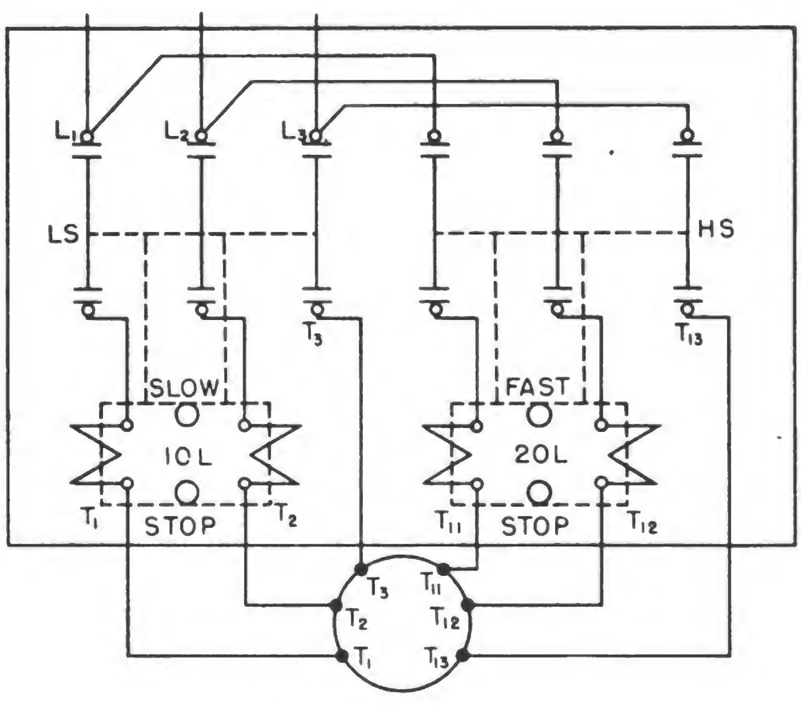


Figure 205.—Across-the-line starter for two-speed two-winding motor.

If the motor is operating on one winding, you can transfer to the other winding. Simply depress the button controlling the contacts which connect the desired winding across the line. The mechanical interlock will open the other set of contacts.

To stop the motor, depress the STOP button located below the FAST button if the motor is running at high speed, or depress the STOP button below the SLOW button if the motor is operating at slow speed.

The overload relays are reset by pressing either the SLOW or FAST button.

A.C. MAGNETIC ACROSS-THE-LINE STARTER

The magnetic across-the-line starter shown in figure 206 is operated by local or remote master switch, or by automatic

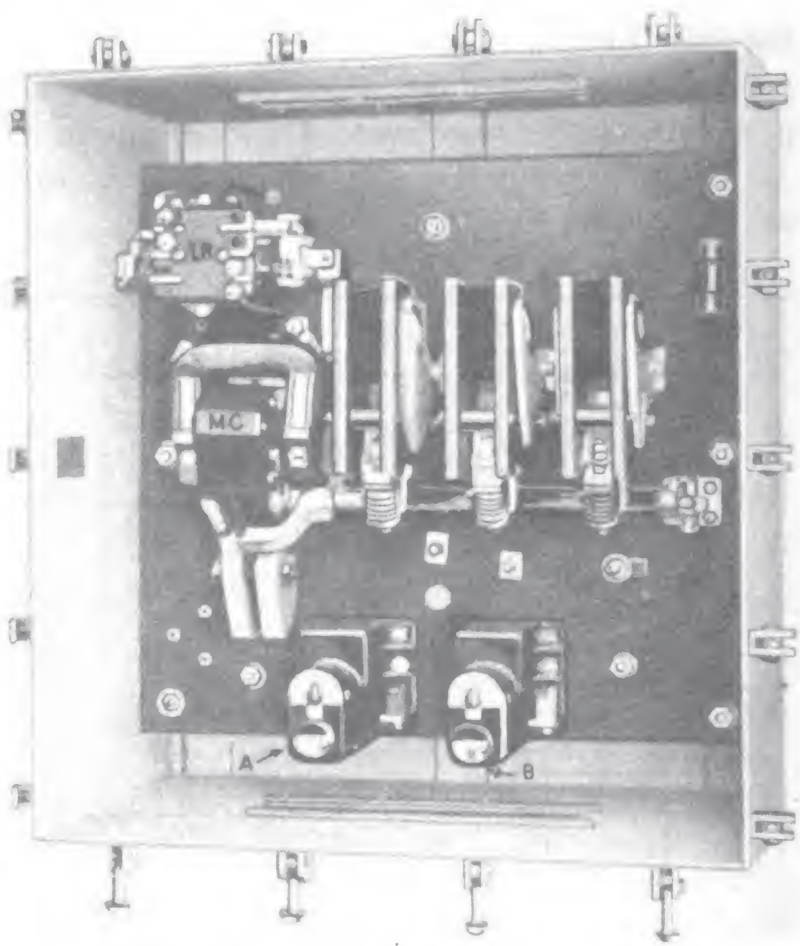


Figure 206.—A.C. magnetic across-the-line starter.

master switches such as pressure or temperature regulators. It consists of a shunt controlled main line contactor *MC*, two overload relays *A* and *B*, and a LATCHING RELAY, *LR*.

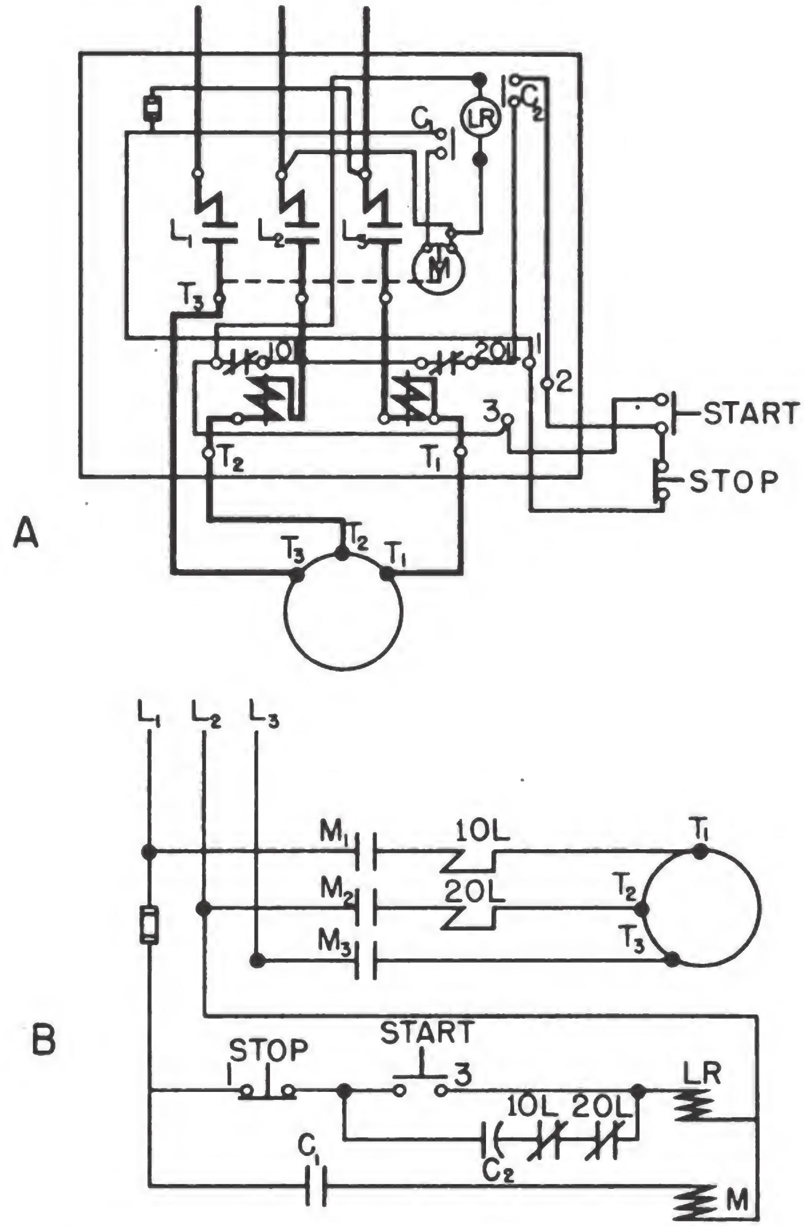


Figure 207.—Wiring diagram of magnetic across-the-line starter with three-wire remote control.

Figure 207*A* is the wiring diagram and 207*B* an elementary wiring diagram of the starter. When the START button is depressed, a circuit is completed from L_1 through the START and STOP buttons and the coil of *LR* to L_3. The coil of *LR* is energized and *LR* operates to close relay contacts C_1 and C_2.

This completes a circuit through coil M. Coil M is energized and closes the main line contacts MC_1, MC_2, and MC_3. Now, the motor is connected directly across the line.

The latching relay controls the circuit to the coil of the main line contactor and prevents false operation of the main contactor under abnormal conditions. Contacts C_1 and C_2 are connected together by a lever which prevents them from opening as the result of a shock. Also, when the latching relay opens, it operates a mechanical latch which prevents the main contactor from closing while it is electrically de-energized.

When the STOP button is depressed, the latching relay is de-energized and contacts C_1 and C_2 open. This de-energizes the coil of the main contactor and the main contacts open.

You will notice that the overload relays are in the control circuit, but are caused to operate by heating elements placed in the main lines. The relays are reset by depressing the reset buttons. The fuse is also in the control circuit and is placed there to protect the control circuit when remote control switches are used.

The starter also gives LOW VOLTAGE PROTECTION. That is, the magnetic contactor will open when the line fails or goes below a certain value. When the voltage is RESTORED to its normal value, the motor WILL NOT start again until the START button is depressed.

The a.c. magnetic contactor has an additional feature not found on a d.c. contactor. The armature of the contactor has a SHADING WINDING. As in the shaded pole motor, this shading winding is a short-circuited copper band or coil placed around a portion of the armature of the coil. It causes the flux in the shaded part of the armature to LAG THE MAIN FLUX. Thus, the armature is never completely demagnetized when the alternating current in the coil goes through its zero value. If the shading winding isn't used, the contactor will have a tendency to open as the current goes through its zero value. It won't open, but it does set up a hum or it tends to chatter.

MAGNETIC REVERSING CONTROLLER

Figure 208*A* is a wiring diagram of a MAGNETIC REVERSING

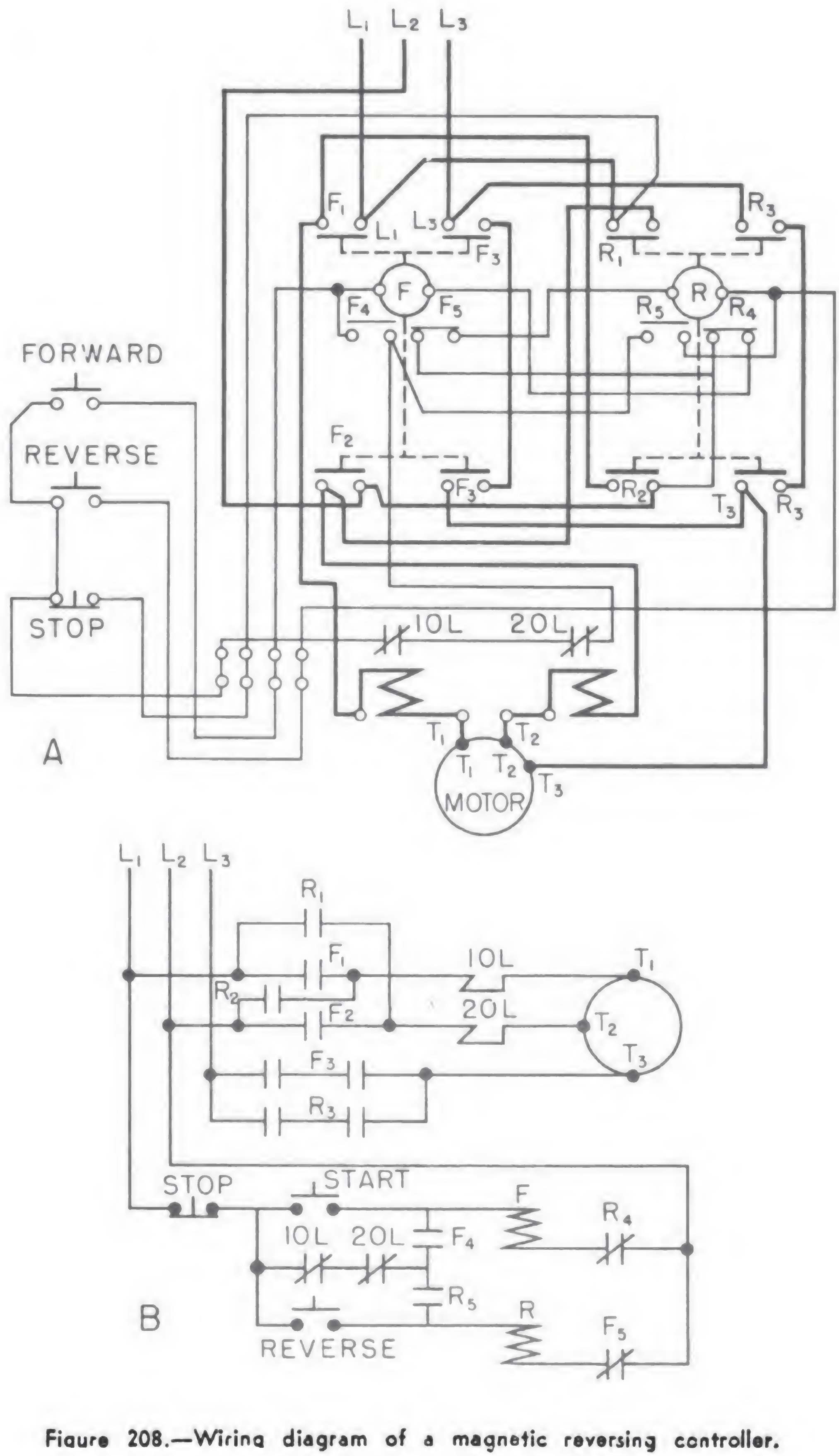


Figure 208.—Wiring diagram of a magnetic reversing controller.

CONTROLLER, and 208*B* is an elementary diagram of the circuit. Its operation is similar to that of the non-reversing type of controller shown in figure 206, except that the reversing type controller is controlled by a THREE BUTTON MASTER switch—FORWARD, REVERSE, and STOP. The forward and reverse buttons are used also for emergency run.

Notice that the controller actually has two magnetic contactors and two sets of contacts. The control circuit of the magnetic contactor F is energized by the forward button and de-energized by the stop button. The control circuit of the magnetic contactor R is controlled by the reverse button and the stop button.

When the forward button is depressed a circuit is completed from L_1 through the forward button and stop button, through the magnetic contactor coil F, and through normally closed contacts R_4 and L_2. Coil F is energized, and the contactor closes main line contacts F_1, F_2, and F_3. Thus the motor is connected directly across the line. T_1, T_2, and T_3 are connected to L_1, L_2, and L_3 respectively.

When coil F is energized and closes the main contactor, it also closes contactor F_4, which completes the holding circuit and permits the forward press button to be released. Then the closed contactor F_5 is opened by a MECHANICAL INTERLOCK.

Depressing the stop button de-energizes coil F, and the main contactor opens contacts F_1, F_2, and F_3, stopping the motor. Contactor F_4 is opened also, and the stop button may be released. Contactor F_5 returns to its normally closed position.

Now if the reverse button is depressed, a circuit is completed from L_1 through the stop button and the reverse button, through the magnetic contactor coil R_1 and normally closed contactor F_5 to L_2. Coil R is energized, and the contactor closes main line contacts R_1, R_2, and R_3. The motor is connected directly across the line, but T_1 and T_2 have been reversed—T_1 and T_2 are connected to L_2 and L_3 respectively—and the motor is reversed.

When R is energized and operates the main contactor, contactor R_5 is closed, and the holding circuit is completed around the reverse button which may be released. Also, normally closed contactor R_4 is opened, preventing coil F from being energized.

Contactors F and R are mechanically interlocked to prevent both closing at the same time. If both should close at the same time, L_1 and L_2 would be short-circuited.

AUTO TRANSFORMER STARTER

An auto transformer starter—also called auto-compensator—is shown in figure 209. It is magnetically controlled. It has

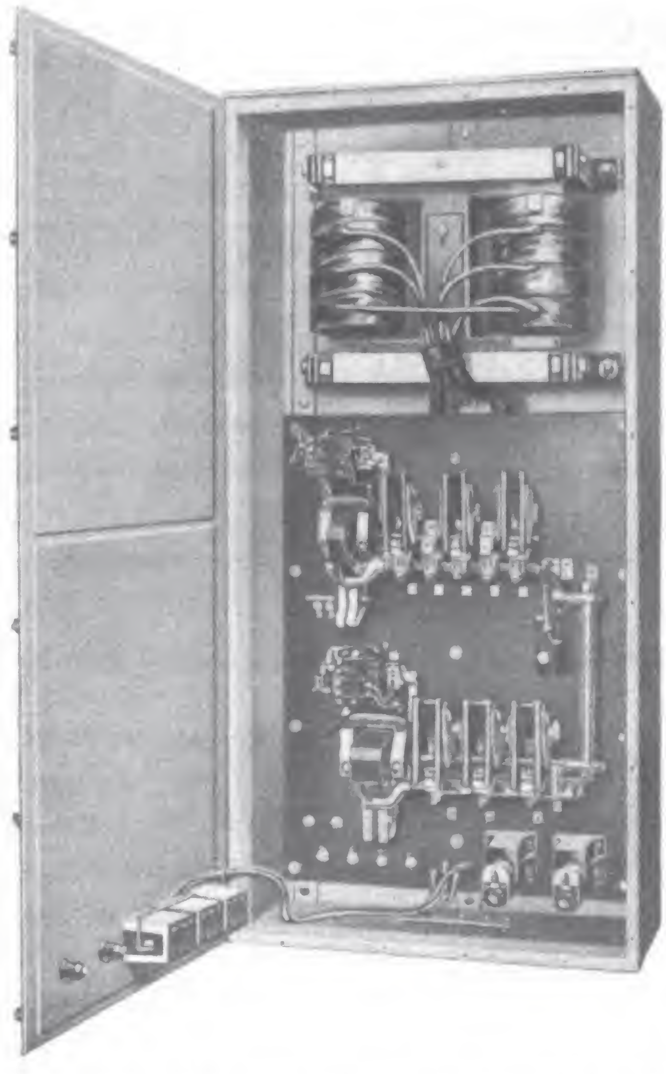


Figure 209.—A.C. magnetic auto transformer starter.

a magnetic starting contactor which, when closed, connects the transformers OPEN DELTA. It also connects the primary terminals to L_1, L_2, and L_3 and connects the motor leads to the secondary taps on the transformers. In this way the motor is started at a reduced voltage.

Figure 210 is a wiring diagram of this auto transformer starter. There are three secondary taps on each transformer, and, in this particular case, the number 3 taps are used. A starting voltage equal to 80% of full line voltage is applied to the motor.

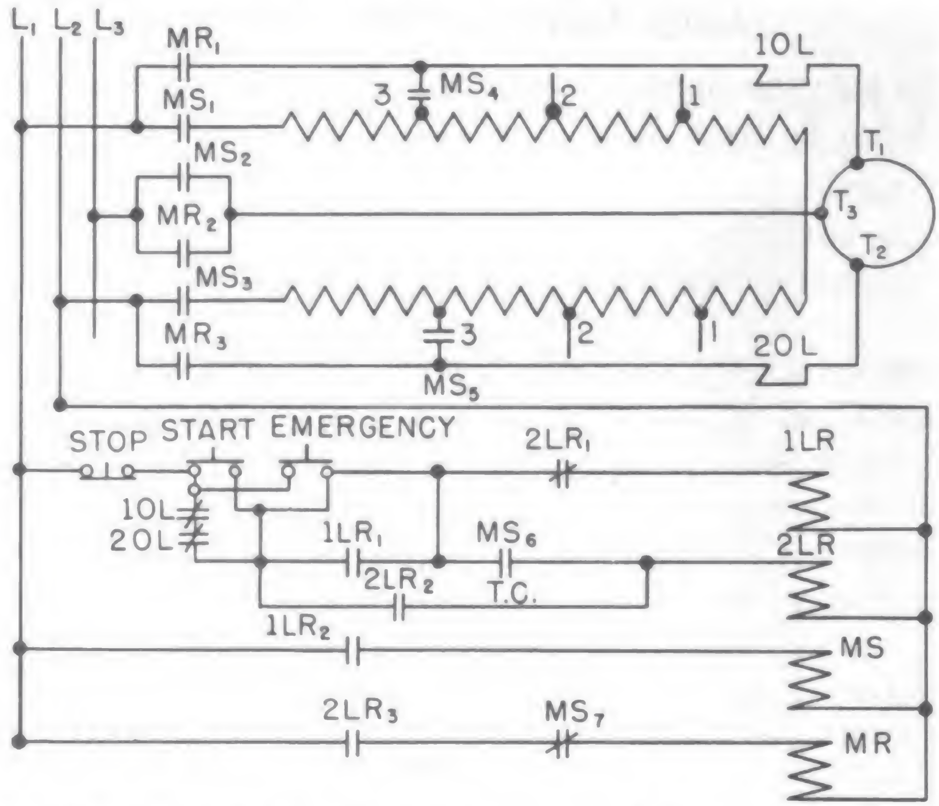


Figure 210.—Wiring diagram for a.c. magnetic auto transformer starter.

By using tap 1 or 2, the starting voltage may be reduced to 50% or 65% of the full line voltage. If tap number 1 on one transformer is used, then tap number 1 on each of the other transformers must be used. The same thing goes for taps 2 and 3.

Now, trace the circuit during the operation of the starter (figure 210).

When the start button is depressed, a circuit is completed from L_1 through the stop button, start button, and latching relay coil *1LR* to L_2. When *1LR* is energized, it closes contactor $1LR_1$ and $1LR_2$. Contactor $1LR_1$ completes the HOLDING CIRCUIT which shunts the start button, and the start button may be released. Contactor $1LR_2$ completes the circuit through contactor coil *MS*.

MS is energized and operates the starting contactor, closing contacts MS_1, MS_2, and MS_3. This connects the auto trans-

former in open delta and to the supply line. At the same time, contacts MS_4 and MS_5 are closed, and the motor is connected to the secondary taps of the transformers. Thus, the motor is started at a reduced voltage, and, since the auto transformers step down the voltage, the primary current is less than the secondary current which the motor draws.

At the same time coil MS closed the starting contactor, interlocks opened contactors MS_7. This prevents MR from becoming energized. Also, the time relay T.C., a mercury dash pot type mechanically connected to the starting contactor shaft, begins to operate. After a predetermined time delay, it closes contactor MS_8. This completes a circuit which connects latching relay coil $2LR$ across the line. The relay operates, closing contactors $2LR_2$ and $2LR_3$ and opening contactor $2LR_1$.

When $2LR_1$ is opened, relay $1LR$ is de-energized and contactors $1LR_1$ and $1LR_2$ open. Opening $1LR_2$ de-energizes starting contactors MS and it opens. The auto transformers are disconnected from the line and the motor. When MS opens, its interlocks close contactor MS_7. This completes the circuit which connects running contactor coil MR across the line. MR is energized and closes contacts MR_1, MR_2, and MR_3. The motor is connected directly across the line.

Emergency run operation is obtained by holding down the EMERGENCY RUN button.

STAR-DELTA STARTING

A reduced voltage may be applied to a motor which normally has a delta connected winding by changing the motor terminal connection during the starting period. If the winding is changed from a delta connection to a star connection, the voltage across the windings is reduced to 57.7% of the line voltage. After the motor is started, the windings are reconnected delta, and the voltage across them is line voltage.

All the phase leads are brought out to the terminal box, so the connection may be easily changed.

Figure 211 is a wiring diagram of a magnetic controller used for star-delta starting. When the start button is depressed, contactor coil M is energized and closes contacts M_1, M_2, and M_3

connecting phase leads T_2, T_4, and T_6 across the line. At the same time, relay R and magnetic contactor S are energized. Contactor S closes contacts S_1, S_2, and S_3 which connect phase leads T_1, T_3, and T_5 together. Now, the motor winding is star connected and connected across the line.

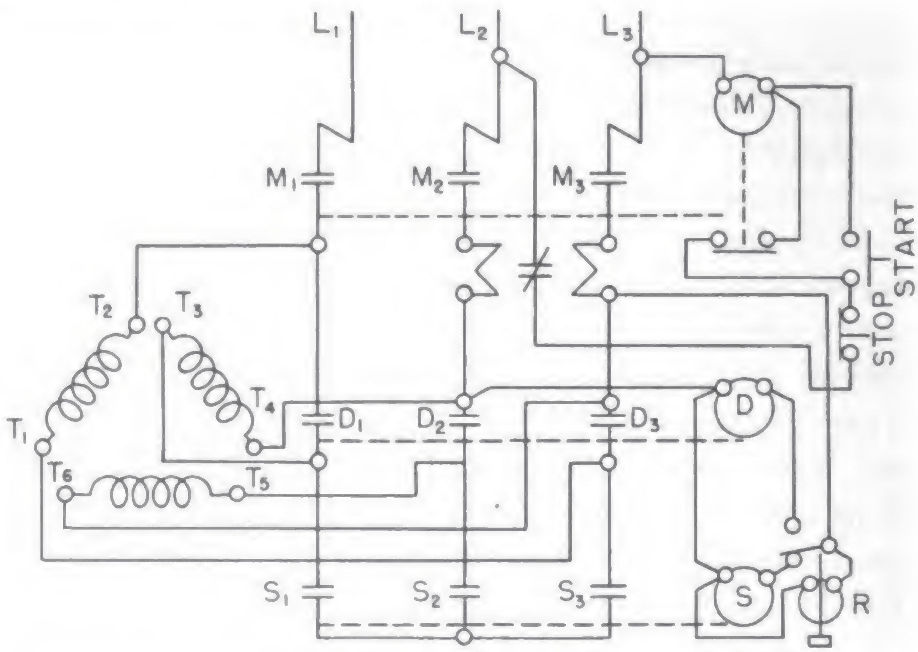


Figure 211.—Wiring diagram for star-delta magnetic controller.

Relay R is a time relay. After a predetermined time delay, it opens the control circuit of contactors S and closes the control circuit of contactor D. Contactor S opens contacts S_1, S_2, S_3. Contactor D closes contacts D_1, D_2, D_3. Contacts D_1, D_2, D_3 connects T_1, T_3, T_5 to T_6, T_2, T_4 respectively and make a delta connection of the stator winding. Contacts M_1, M_2, and M_3 remain closed so that the motor is connected across the line.

MAINTENANCE OF CONTROLLERS

The most important rule to remember when taking care of controllers is—BE SURE THE CONTROLLER IS DISCONNECTED FROM THE POWER SOURCE BEFORE TOUCHING ANY OF THE OPERATING PARTS.

Now that you are protected you can go ahead with your work. And of course the first thing you should do to obtain maximum efficiency from any controller is keep it CLEAN. Keep it free

from dirt, dust, grease or oil, both inside and out. Clean the operating mechanism and contacts with a dry cloth, or with a vacuum cleaner. Small and delicate mechanical parts may be cleaned with a small, stiff bristle brush and carbon tetrachloride.

If individual instruction sheets for a device indicate bearing surfaces are to be lubricated, the bearing surfaces should receive a few drops of light oil, and all excess oil should be wiped off. In general, bearings which operate on a shaft or pin require lubrication. But knife edge bearings and plunger type armatures—any bearings which may become gummed up—SHOULD NOT BE OILED.

COPPER CONTACTS are used for most heavy duty power circuits and, in many cases, in relay and interlock circuits. They should be inspected regularly. If projections extend beyond the contact surfaces, the contacts are pitted or coated with copper oxide. They should be dressed down with fine sand paper.

WELDING of copper contacts sometimes occurs. In spite of all precautions, low voltage is the most common cause. Welding may also result from overloads, low contact pressure resulting from wear or weak springs, loose connections, or excessive vibration. If welding occurs, it is an indication of trouble in the electrical system. The contacts will have to be replaced, but it is useless to replace them unless the cause of the welding is found and corrected.

CARBON CONTACTS are used where it is essential that a contactor always open when it is de-energized and not under any circumstances weld closed. They are used only when necessary because the current carrying capacity of carbon per square inch of contact surface is low, and therefore the contacts must be relatively large.

SILVER CONTACTS are used extensively in pilot and control circuits, on relays, interlocks, master switches, and so on. They are used also on smaller controllers, and on heavy duty jobs when the contactors remain closed for a long period of time with infrequent operation. Silver contacts are used because silver oxide doesn't have the insulating qualities of copper oxide, and silver, therefore, insures better contact.

Silver contacts seldom require dressing and SHOULD NOT BE DRESSED unless sharp projections extend beyond the contact sur-

face. The contacts should be renewed when the wear allowance specified by the individual instruction sheet has been used up or when the contact face material has been worn away. If silver contacts are inactive for any time they should be cleaned with a cloth and carbon tetrachloride before they are put back in service.

BLOWOUT COILS seldom wear out or give trouble when used within their rating. However, if they are required to carry excessive currents, the insulation becomes charred and fails, causing flash-overs and failure of the device.

ARC SHIELDS are constantly subjected to the intense heats of arcing and may eventually burn away, allowing the arc to short circuit to the metal blowout pole pieces. Therefore, arc shields should be inspected regularly and renewed before they burn through.

ARC BARRIERS provide insulation between electrical circuits and must be replaced if broken or burned to a degree where short circuits are likely to occur.

LOOSE CONNECTION—now there's a subject about which you should need no instruction. The importance of having clean, tight electrical connections cannot be over-emphasized. Where it is practical, it is a good idea and a common practice to solder electrical connections.

EXCESSIVE SLAM on closing, particularly on a.c. magnet operated devices, will eventually damage the laminated face of the magnet armature and may damage the shading coil.

High voltage on the coil or the incorrect coil for the voltage may cause excessive slam. In the case of high voltage, correct it at the power source. If the voltage is correct, check the coil numbers against the service plans for the device and see if they agree with the nameplate voltage. If not, replace the coil with the proper coil.

If a.c. magnets CHATTER, check the shading coil and replace if broken. A temporary repair can sometimes be made by soldering a jumper over the break.

A MAGNETIC HUM on a.c. magnets is an indication that the magnet armature is not properly sealed when it closes. In addition to the broken shading coil, magnetic hum may be caused by—dirt, grease or other foreign matter on the magnet face;

misalignment of the armature; binding caused by a bent armature; low voltage; too much spring pressure on the contacts.

MAGNET COILS should be kept dry. Wet coils should always be dried out before using. They may be dried by baking them in an oven at 110° C to 125° C. The length of time in the oven depends upon the size of the coil.

Protecting resistors are sometimes automatically inserted in series with the coil by means of auxiliary contacts when the magnet operates. This is to protect the coil from overheating. If excessive heating of the coil is apparent, the resistor should be checked for shorts, and you should make sure the auxiliary contactor is inserting the resistor in the circuit.

Low voltage, sticking armature, or too much spring pressure on the contacts may prevent the magnetic gap from closing properly; the result often is a burned out coil.

Always handle coils carefully. Don't pick them up by their leads.

A little attention to the controllers at the right time can save you lots of trouble and work.

How Well Do You Know--

ELECTRICIAN'S MATE 2c

QUIZ

CHAPTER 1

A QUICK REVIEW

1. The unit of current flow is the (coulomb) (ampere) (second) (EMF).
2. A 100, a 50, and a 25 ohm resistor are connected in parallel. If an emf of 70 volts is applied to the 25 ohm resistance, how much current flows through the three resistors?
3. An ammeter with a 0-5 ampere range has an internal resistance of .01 ohms. What resistance must you use, and how must you connect it to extend the range to 0-10 amperes?
4. A 1,000 ohm per volt voltmeter has a range of 0-100 volts. What resistance must you use, and how must you connect it, to extend the range to 0-200 volts?
5. A potential of 220 volts is applied to a lighting circuit. What are the IR drops about the circuit?
6. You are holding a coil in your hand PALM UP. Your thumb is pointing toward the north pole. What direction is the current flowing in the coil?
7. The unit of capacitance is the (Henry) (Coulomb) (Farad) (Abohm).

CHAPTER 2

KIRCHHOFF'S LAWS

1. Four resistances, 30, 45, 90, and 180 ohms, are connected in series. The IR drop across the 90 ohm resistor is 15 volts. What is the circuit EMF?
2. Three resistors, 100, 50, and 25 ohms, are connected in parallel. A 1 ampere current flows through the largest resistance. What are the currents through the other two resistors, the current flowing away from the circuit, and the applied EMF?

CHAPTER 3

MEASUREMENT INSTRUMENTS

1. The .... and .... are two types of meters commonly used with A.C.

2. Make a schematic diagram showing how to connect potential and current transformers into the circuit.
3. What precaution must be observed in using current transformers?
4. What precaution must be taken with a potential transformer?
5. Make a circuit diagram of a single phase wattmeter and indicate circuit connections.
6. Do wattmeters indicate (true power) (apparent power) (average power)?
7. A polyphase wattmeter has how many sets of movable coils? Stationary coils?
8. In a watt hour meter the rpm of the motor is proportional to the ....

CHAPTER 4

GENERATORS—ARMATURE WINDING

1. Make a schematic diagram of a series, shunt cumulative compound, differentially compound, and separately excited generator connections.
2. What is the meaning of a "full pitch" in armature windings?
3. Make a sketch of a lap winding.
4. The coils of a lap winding lie in slots 3 and 11. What is Yb?
5. In a 4-pole lap wind, what part of the distance around the armature does each winding reach?
6. In order to obtain a balanced armature voltage, Yf and Yb must be (both odd numers)• (both even numbers) (one odd and one even).
7. Make a sketch of a wave winding.
8. You have a 16 slot armature and wish to place a wave winding on it. Why cannot Yf and Yb be 8?
9. You have a simplex wave winding with the coils lying in slots 1–10–17–26–33–8–15–24–31. Give Yb and Yf?
10. How many current paths in a wave winding?
11. A 4-pole wave wound armature requires how many brushes?
12. What is the purpose of a dummy coil in a wave winding?
13. What is the basic difference between a simplex and a multiplex winding?
14. What is a commutator pitch in a triplex winding?
15. What is the advantage of a 450 ampere triplex over a simplex of the same current capacity?
16. In a generator if you increase the paths you (increase) (decrease) the voltage and (increase) (decrease) the current.

CHAPTER 5

GENERATOR—COMMUTATION

1. In a generator, what is the neutral plane?
2. What must be the position of the brushes in respect to the neutral plane to produce ideal commutation?
3. What will happen if the brushes and neutral plane are not in the proper relationship?
4. What are the three requirements of ideal commutation?
5. What effect does self-induction have on the current in commutator coils?
6. What does the voltage of self-induction do to ideal commutation?
7. What is the relationship of the directions of the field flux to the flux of a loaded armature?
8. What effect does the combination of field and loaded armature flux have on the neutral plane?
9. Increasing the load on a generator causes you to shift the brushes (in the direction) (away from the direction) of rotation.
10. A changing load will cause you to .... the brushes each time the load changes to prevent ....
11. List the four devices used to overcome the effect of the emf of self-induction and armature reaction.
12. Slatted pole pieces weaken the armature field by ....
13. What effect has a laminated pole tip on the distorted flux field?
14. What is the relationship of the physical position of interpoles to the mechanical neutral plane?
15. What is the relationship of the flux strength of the interpole to the flux produced by the emf of self-induction?
16. How do the interpoles overcome the effect of armature reaction?
17. How are the interpoles connected into the armature circuit?
18. What is the direction of the current flow in armature compensating windings?
19. How are the compensating windings connected into the armature circuit?

CHAPTER 6

D.C. GENERATORS—VOLTAGE REGULATION AND CONTROL

1. Voltage regulation refers to ....
2. Voltage control is ....
3. A generator has a no load terminal voltage of 450 volts, and a full load voltage of 420 volts. What is the percent of regulations?

4. What three factors influence the terminal voltage of a shunt generator running at a constant speed?
5. Make a sketch of the terminal voltage output of a shunt wound generator with a drooping characteristic.
6. What is the usual method of regulating the terminal voltage of a shunt generator?
7. What is the character of the series field in a flat compound generator?
8. If the series field of a compound generator has enough turns to cause the voltage to rise with increased load, the generator is said to be (flat) (under) (over) compounded.
9. What is the terminal voltage characteristic of a differentially compounded generator?
10. What type of d.c. generator is installed in most ships? What is the characteristic of its winding?

CHAPTER 7

D.C. MOTORS

1. List the factors used in classifying motors.
2. List the 6 degrees of enclosure used with many motors.
3. What is the difference between a continuous duty and an intermittent-duty motor?
4. What effect does armature reaction have upon the field flux in a motor?
5. To compensate for flux distortion in a motor, you shift the brushes (backward) (forward).
6. How do the commutation difficulties of a d.c. generator and motor compare?
7. What is the relative polarity of main poles and interpoles in a d.c. generator?
8. What devices other than interpoles are used to improve commutation in motors?

CHAPTER 8

MORE ABOUT D.C. MOTORS

1. If a motor turns 1,750 RPM with no load, and 1,600 RPM with load what is its speed regulation?
2. A shunt motor is connected to a 200 volt line, draws 5.4 amperes, and turns 1,750 RPM with no load. When fully loaded, it draws 30.4 amperes. The field resistance is 500 ohms and armature resistance is 4.4 ohms. What speed does the motor turn when loaded?

3. A series motor has a torque of 50 lb.-ft. with 25 amperes; what will the torque be at 30 amperes?
4. A 220 volt series d.c. motor turns 1,250 RPM when the current is 4 amperes. What will be the RPM when the current is 12 amperes, assuming the flux is doubled at 12 amperes? The resistance of armature and brushes is 0.8 ohms, and field 1.2 ohms.
5. What precautions must be taken when using series motors? Why?
6. What is the nature of the starting torque characteristic of a compound motor as compared to a series and shunt motors.
7. What type of a winding produces a nearly constant speed?
8. In differently compounded motors, which field is shorted out during starting? Why?
9. What is the nature of the speed curve for shunt and compound motors from no load to load?
10. When will the speed of a series motor begin to drop?
11. In shunt and compound motors, which speed control method is most efficient? What is the usual permissible range of control?

CHAPTER 9

STARTERS & CONTROLLERS FOR D.C. MOTORS

1. List four uses of the motor controller.
2. List 5 types of controllers classified as to degree of enclosure.
3. List 6 types of controllers, classified according to their construction.
4. In d.c. controllers, identify the functions of the following parts:
   a. Starting resistance
   b. Low voltage coil
   c. Series overload coil
   d. Blowout coil

CHAPTER 10

MAGNETIC CONTACTORS

1. What is the function of the accelerator contactors in figure 91?
2. What is the basic difference between a magnetic and a manual contactor?
3. What is the difference in the solenoids used with shunt and series contactors?
4. What is the function of auxiliary contacts with shunt contactor in figure 92?
5. In figure 91, what is the function of auxiliary contacts "H"?
6. When two or more remote start-stop buttons are connected to a single magnetic contactor, the buttons are connected in (series) (series parallel) (parallel).

CHAPTER 11

OVERLOAD PROTECTION

1. List three methods of obtaining overload protection.
2. In figure 97, list the sequence of operation in the event of an overload.
3. How does an overload current trip the contacts in figure 98?
4. Why are the three steps of starting resistance necessary with magnetic contactors like the ones in figure 99?
5. How could the contactors of figure 99 be used as a speed regulator?
6. In figure 100, how is the starting resistance removed from the circuit?
7. What is the reaction of a series contactor to a high and low current?
8. How does the size of the air-gap in figure 102 influence the operation of the contactor?
9. In the double lock-out contactor of figure 103, which coil closes and which coil holds the contactor open?
10. Series contactors are often called current limit starters. Why?

CHAPTER 12

CIRCUIT BREAKERS

1. In figure 106, which contacts open first?
2. What purpose do the auxiliary contacts in figure 106 serve?
3. What type of a trip coil is shown in figure 107?
4. What is the sequence of action in opening the circuit breaker in figure 107?
5. How does the operation of an undervoltage circuit breaker differ from an overload circuit breaker?
6. How many coils are used in a reverse current circuit breaker? Name them.
7. Where are reverse current circuit breakers used?
8. What current energizes the solenoid in figure 108?
9. In figure 108 what will happen if the current falls below a predetermined value?
10. In figure 109, how does the motor become a brake?

CHAPTER 13

ALTERNATING CURRENTS

1. The peak emf of a generator is 440 volts. What is its instantaneous value at 30°, 50°, 80°?

2. A generator has 6 poles. How many electrical degrees in one rotation?
3. If the generator in question 2 is turning 120 rps, what is the frequency?
4. How is an ampere of a.c. compared to an ampere of d.c.?
5. An a.c. generator has a terminal emf of 440 volts. What are the peak and average values?
6. Two currents are out of phase by 90°. The emf of one is 90° and the other 100°. What is the combined voltage?

CHAPTER 14

REACTANCE

1. A 440 volt circuit contains an inductance of .6 henries. The frequency is 60 cycles. Neglecting the resistance, how much current will flow in the circuit?
2. An inductance causes the current to (lag) (lead) the voltage.
3. In drawing a vector diagram of an inductive circuit, which direction will the phase angle be rotated?
4. In an inductive circuit, the IXL component is 120 volts, and IR 100 volts. What is the circuit E? What is the power factor?
5. In a capacitive circuit, what is the relationship between the current and voltage?
6. How does a condenser charge?
7. What is the comparative reaction of a condenser to d.c. and a.c.?
8. A condenser has a capacity of 20 mf. What is its reactance to a 60 cycle current? If the emf is 220 volts, what current will flow if resistance is zero?

CHAPTER 15

IMPEDANCE

1. A circuit contains an inductance of .1 henry and a resistance of 36 ohms. The frequency is 60 cycles and the emf 220 volts. What is the impedance and what current will flow?
2. In question 1, what is the phase angle?
3. A circuit contains a resistance of 40 ohms, an inductance of 1.0 henry, and a condenser of 8 mf. The frequency is 60 cycles and the line emf is 440 volts. Find the current and the power factor.

4. A resistance of 20 ohms, an inductance with an XL of 15 ohms, and a condenser with an XL of 10 ohms are connected in parallel across a 220 volt, 60 cycle line.
   Find:
   - *a*. Current through each leg.
   - *b*. Total current.
   - *c*. Total power.
   - *d*. Phase angle.

CHAPTER 16

POWER

1. In an a.c. circuit containing a resistance only, why cannot $EM \times IM$ equal the true power of the circuit?
2. Show that E eff $\times$ I eff gives average power.
3. Explain "wattless power."
4. Find the true power in a 225 volt, 60 cycle circuit containing a resistance of 20 ohms and an XL of 15 ohms. What is the power factor?

CHAPTER 17

ALTERNATING CURRENT GENERATORS

1. What advantages do polyphase currents have over single phase currents?
2. A balanced 3 phase generator has a terminal voltage of 220 and a line current of 10 amperes. Find the total power if the phase angle is 30° lagging.
3. Why is it necessary to use the KVA system in rating alternators rather than KW?
4. A low speed generator uses a .... pole rotor and a high speed generator uses a .... rotor.
5. What method of cooling is used with turbo type generators?
6. Which type of generator is usually used with direct connected alternators for sizes greater than 500 KVA?
7. How does a lagging power factor influence the terminal emf of an alternator?
8. Voltage regulations of alternators are inherently (better) (poorer) than d.c. generators.
9. How will the starting of an a.c. motor affect the terminal voltage of an alternator?
10. Why is manual voltage control unsatisfactory with alternators?

11. How is automatic voltage control of an alternator accomplished?
12. What is the purpose of an equalizing reactor?

CHAPTER 18

PARALLEL OPERATION OF ALTERNATORS

1. Why must the phase of the incoming alternator be in the same direction as the running alternator when the live switch is closed?
2. In using three incandescent lamps to indicate when to parallel alternators, tell what the following conditions indicate —
   a. Flickering lamps.
   b. Bright lamps.
   c. All dark.
3. Where is it advisable to use the two bright and one dark lamp method in paralleling alternators?
4. What information is revealed by the synchroscope?
5. When using a synchroscope, what is the proper interval to close the paralleling switch?
6. How may an alternator be made to carry more load?
7. Why does increasing the power on a paralleled alternator pull the alternator out of synchronism?

CHAPTER 19

TRANSFORMERS

1. A primary and a secondary terminal of a transformer are said to be of like polarity. What does it mean?
2. What do terminal markings H and X mean?
3. Determining the polarity of a transformer is known as ....
4. Make a diagram to indicate a series connection of transformers.
5. What is an advantage of using a delta connected transformer system?
6. What type of transformer connection is used to obtain high voltage?
7. How many windings on an auto transformer?
8. Which portion is considered as the secondary in an auto transformer?
9. Where are three-phase transformers used?
10. How are potential transformers connected into circuits? Current transformers?
11. What precaution must be observed in using current transformers?

CHAPTER 20

A.C. MOTORS

1. What advantages over a d.c. motor are present in an induction motor?
2. For what type of service are d.c. motors best suited?
3. What causes the magnetic field to rotate in an induction motor?
4. What is the synchronous speed of a 4-pole machine powered by a 120-cycle current?
5. What is the nature of the windings in a squirrel cage rotor?
6. What is the electrical connection between the line and rotor of a squirrel cage motor?
7. Why cannot the rotor of a squirrel cage motor turn at the same rpm as the rotating field?
8. What is "slip"?
9. Which squirrel cage motor will have the better speed regulation, a high or low resistance rotor winding?
10. Why is the starting current of an induction motor very high?
11. How may the high starting current of a squirrel cage rotor be reduced?
12. What advantage does a wound rotor motor have over a squirrel cage rotor?
13. How may squirrel cage motors be designed for speed adjustment?
14. In a synchronous motor (a.c.) (d.c.) is applied to the stator and (a.c.) (d.c.) to the rotor.
15. How are synchronous motors usually constructed to facilitate starting?
16. How is a synchronous motor used to improve power factor?
17. What is the purpose of the second winding in a split phase motor?

CHAPTER 21

A.C. CONTROLLERS

1. Why are starters necessary with large induction motors?
2. Name the two types of a.c. motor starters commonly used.
3. Which type is most commonly used? Why?
4. What types of protection are built into across-the-line starters?
5. In across-the-line two speed starters, which speed is used to start the motor?
6. What advantage is experienced in starting a delta-wound motor as a star connected and then reconnecting the motor delta once speed is reached?
7. What precaution must you always observe when servicing a controller?

ANSWERS TO QUIZ

CHAPTER I

A QUICK REVIEW

1. Ampere.
2. Approximately 5 amps.
3. .01 ohms, as a shunt.
4. 100,000 ohms, in series.
5. 220 volts.
6. Toward you at the top, away at the bottom of the coil.
7. Farad.

CHAPTER 2

KIRCHHOFF'S LAWS

1. 57.5 volts.
2. 2 amps. and 4 amps., 7 amps., and 100 volts.

CHAPTER 3

MEASUREMENT INSTRUMENTS

1. Iron vane and electrodynamometer.
2. Check your answer with figures 24 and 25.
3. Short and ground the secondary before removing ammeter from the secondary.
4. Close the secondary through a high resistance.
5. Check your answer with figure 27.
6. True power.
7. Two sets of each.
8. Power.

CHAPTER 4

GENERATORS—ARMATURE WINDING

1. Check diagrams with figure 29.
2. Both legs of a coil are in the center of opposite field poles at the same instant.
3. Check drawing with figure 33 or 34.
4. 8.
5. Approximately one fourth the distance.
6. Both odd numbers.
7. Check your drawing with figure 36.
8. The coil will close on itself after one round.
9. $Yb = 9$. $Yf = 7$.
10. Two.
11. Two.
12. To balance the armature.
13. A multiplex has two or more parallel windings and a simplex has a single winding only.
14. $Yc = 3$.
15. Wires may be smaller in a triplex current divided between the three windings.
16. Decrease voltage—increase current.

CHAPTER 5

GENERATOR—COMMUTATION

1. The plane where no emf is induced.
2. Brushes must lie along the neutral plane.
3. Arcing will burn brushes and score armature.
4. No voltage—no current—no sparking in the shorted coil.
5. To keep the current flowing after the coil has passed from under a pole.
6. Causes current to flow while the brushes are in the neutral plane.
7. They are at right angles to each other.
8. Shifts the neutral plane in the direction of rotation.
9. In the direction.
10. Shift—sparking.
11. Slotted pole pieces—laminated pole tips—interpoles—compensating windings.
12. By placing a high reluctance air gap in the path of the flux.
13. The half amount of iron reduces the flux concentration at the pole tips by one half.
14. They lie along the mechanical neutral plane.
15. Made exactly equal.

16. The polarity of the interpole is the same as that of the next main pole, thus producing cancellation of the armature flux.
17. In series.
18. Opposite to the armature current.
19. In series.

CHAPTER 6

D.C. GENERATORS—VOLTAGE REGULATION AND CONTROL

1. Any change in generator terminal voltage caused by a change of load.
2. Any external adjustment used to regulate the generator voltage.
3. Approximately 7%.
4. 1. IR drop in armature.
   2. AR drop caused by armature reactance.
   3. Decreased field excitation.
5. Check your sketch with figure 66.
6. Insert a rheostat in series with the shunt field.
7. Series field has just enough turns to compensate for the loss of flux of the shunt field.
8. Over.
9. Terminal.
10. Stabilized shunt. The shunt winding is just enough to allow a voltage regulation of 12%.

CHAPTER 7

D.C. MOTORS

1. *a*. Degree of enclosure.
   b. Method of cooling.
   c. Speed.
   d. Duty.
   e. Type of field winding.
   f. Voltage.
2. Open—dripproof—semi-enclosed—enclosed—waterproof—submersible.
3. A continuous duty motor can be operated for an indefinite period without overheating. An intermittent duty motor can be operated for a limited time only.
4. It distorts the field flux opposite to the direction of armature rotation.

5. Backward.
6. They are the same.
7. The interpole has the same polarity as the main pole in back of it.
8. Laminated pole tips, slotted pole pieces, compensating windings.

CHAPTER 8

MORE ABOUT D.C. MOTORS

1. Approximately 8%.
2. Approximately 1,610 RPM.
3. Approximately 72 lb.-ft.
4. Approximately 578 RPM.
5. Never operate without load.
   Motor will run away.
6. Less than series, greater than shunt.
7. Differentially compounded.
8. *a.* Series field.
   b. To eliminate the danger of motor starting in reverse direction.
9. Nearly flat.
10. When the saturation point of the iron is reached.
11. Field control. About 25%.

CHAPTER 9

STARTERS & CONTROLLERS FOR D.C. MOTORS

1. Starting, stopping, reversing, and changing speed.
2. Open, semiprotected, protected, dripprooof, and waterproof.
3. Across-line switch, face panel, drum switch, drum controller, pneumatic contactor, and magnetic contactor.
4. *a.* To reduce the current through the motor when starting.
   b. To open the circuit if the voltage falls too low.
   c. To open the circuit if the motor draws too much current.
   d. To blow out the air formed when the contacts open.

CHAPTER 10

MAGNETIC CONTACTORS

1. To cut the starting resistance out of the circuit.
2. A magnetic contactor is just an across-the-line switch activated by a solenoid rather than by hand.

3. Shunt solenoid has many turns of fine wire; series solenoid has few turns of heavy wire.
4. To insert a resistance in series with solenoid in order to reduce the current once the contactors have been closed.
5. To energize the holding coil after the start button has been released.
6. Parallel.

CHAPTER 11

OVERLOAD PROTECTION

1. Fuse, magnetic relays, thermal relays.
2. *a.* High current operates overload relay.
   b. Shunt coil is deenergized.
   c. Main contactor opens cutting off the current.
   d. Overload relay drops back to normal, but main contactors remain open until start button is pressed.
3. *a.* Overload coil raises the plunger and trips the main contactors.
   b. Holding coil on relay keeps circuit open until cause of overload is removed.
4. The three steps provide a means for removing the series starting resistance as the motor gains speed.
5. By making the resistance of sufficient wattage rating to withstand the heat dissipation. The three steps then could be used as a three step speed regulator.
6. Contactor 3R closes and shorts the resistance out.
7. When the line current exceeds a predetermined value, the contactor opens. When it falls below this value, it closes.
8. Increasing the air gap causes the contactor to close at a lower value of current.
9. Coil *D* closes, and coil *C* holds it open.
10. Because the operation of the accelerating contactor depends upon the value of armature current.

CHAPTER 12

CIRCUIT BREAKERS

1. Main contact *A*.
2. They reduce the current after the main contactor has opened and cause the greatest arc to appear at the small carbon contacts.
3. Series.
4. An over-load current lifts the plunger, the plunger trips the tugger, and the contacts fly open.

5. The plunger is held in position by a solenoid as long as the current is normal. When an undervoltage appears, the pull of a spring overcomes the pull of the solenoid and trips the tugger.
6. Two—potential and current coils.
7. Charging panels for storage batteries and on switch boards for paralleling generators.
8. Motor armature current.
9. A spring pulls the brake shoes against the brake drum.
10. A set of contactors places a low resistance across the motor terminals. The load on the motor tends to keep the motor turning, inducing a high current in the armature, and the motor then acts as a generator.

CHAPTER 13

ALTERNATING CURRENTS

1. 220 volts, 325 volts, 433 volts.
2. 1,080.
3. 360 cycles.
4. An ampere of a.c. must produce the same heating effect as an ampere of d.c.
5. 623 volts peak, 396 average.
6. 134.2 volts.

CHAPTER 14

REACTANCE

1. 3.45 amperes.
2. Lag.
3. In a counterclockwise direction.
4. 156.2 volts. .64 (50° lagging).
5. Current leads the voltage.
6. Electrons enter one plate and leave at the other.
7. A condenser acts as an open circuit to d.c. but will conduct a.c.
8. 134 ohms. 1.68 amperes.

CHAPTER 15

IMPEDANCE

1. Z is 52.3 ohms. 4.2 amperes.
2. 46.5° lagging.

3. 7.3 amperes. .667 (48°8′ lagging).
4. *a.* IR is 11.0 A. I_{xl} is 14.7A. I_{xc} is 22.0.
   b. I_t is 13.0 A.
   c. P_t is 2860 watts.
   d. Phase angle is 68°6′ leading.

CHAPTER 16

POWER

1. Because EM × IM gives peak, instantaneous power only.
2. .707 × .707 = .4998 or 49.98%.
3. In a pure inductive circuit, the inductance returns as much power to the circuit as it receives; therefore the average input is zero.
4. 1215.0 watts. .798 (37° lagging).

CHAPTER 17

ALTERNATING CURRENT GENERATORS

1. Smoother power, less pulsation; require smaller generator and less copper.
2. 3,290 watts.
3. The I^2R loss in a generator armature is independent of the power factor, but the output of a generator in *KW* is dependent on the power factor. Thus unless the machine is of unity power factor, the *KW* output must always be less than the *KVA* rating, or the generator will burn out.
4. Salient—turbo.
5. Forced circulation.
6. Turbo-type.
7. Maximum voltage is not reached until the armature coil has passed beyond the center of the field coil. Any further increase in lag will reduce emf still further.
8. Poorer.
9. Starting current of an a.c. motor is 6 to 8 times operating current and of low power factor, contributing further to reducing emf.
10. Too slow and not accurate enough.
11. By using variable resistors in the alternator field activated by the alternator terminal voltage.
12. To keep the power factors of paralleled alternators equal.

CHAPTER 18

PARALLEL OPERATION OF ALTERNATORS

1. Opposite phase will result in a short circuit; partial phase will cause incoming generator to run as a motor.
2. *a*. Incorrect frequency.
   b. Out of phase.
   c. Correct instant to close switch.
3. With high speed turbo-type alternators.
4. The relative frequency of operating and incoming generator.
5. When needle is moving slowly in the FAST direction, and just before it reaches exact synchronism.
6. By increasing the power on the prime mover.
7. Because an alternator once in step tends to remain in that condition. Increased power results in increased load, not speed.

CHAPTER 19

TRANSFORMERS

1. The terminals are maximum positive or maximum negative at the same instant.
2. *H* indicates the high voltage side, *X* the low voltage winding.
3. Phasing out.
4. Check your answer with figure 165.
5. One transformer, if damaged, may be removed from the circuit and the system will operate on approximately 58% of full capacity.
6. Star.
7. One.
8. The portion between the top and either line terminal.
9. In starting induction motors.
10. Across-the-line. In the line.
11. Never open secondary circuit.

CHAPTER 20

A.C. MOTORS

1. It possesses no commutator or brushes; therefore, most of the troubles are eliminated.
2. Constant speed.

3. As the changing value of the current progresses through the windings, the maximum field strength follows the maximum value of current, thus the field is caused to sweep or rotate about the stator.
4. 3,600 rpm.
5. Bars of copper or aluminum are inbedded in a laminated iron coil. The bars are welded to copper aluminum rings on either end of the rotor.
6. Induction only.
7. If the rotor were to turn at the same speed, no induction in the rotor could take place, because no lines of force would be cut.
8. The difference between the rotor speed and the synchronous speed.
9. Low resistance.
10. At low speeds of rotation the field sweeps across the armature bars many times a second. As the speed of rotation increases, the rate of cutting is lower and the current falls.
11. By inserting resistance in series with the bars.
12. The starting resistance may be removed once the motor is up in speed.
13. By designing the stator so a variable number of field poles may be used.
14. a.c.—d.c.
15. Rotors contain a squirrel cage winding; and once up in speed, the d.c. field is excited and the motor locks in step.
16. By connecting the motor without load in parallel with the line. Under-exciting the d.c. field produces a lagging power factor, and over-exciting a leading power factor. The d.c. field is over-excited just enough to correct the lagging factor of the circuit.
17. To aid in starting the motor.

CHAPTER 21

A.C. CONTROLLERS

1. To reduce the starting current and thus protect the lines.
2. Resistance type, and auto transformer.
3. Auto transformer. Gives the lines more protection.
4. Overload, low voltage.
5. High and then switched to low if desired.
6. Starting voltage reduced to about 58°.
7. Be sure it is disconnected before touching any of its parts.

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